Essays in Industrial Organization and Experimental Economics

Dissertation
for the Faculty of Economics, Business Administration and Information Technology of the University of Zurich

to achieve the title of
Doctor of Economics

presented by

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from Zurich

approved at the request of

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Zurich, October 22, 2008

the Dean: Prof. Dr. Dr. Josef Falkinger

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Preface

In writing this dissertation, I enjoyed the encouragement and support of many people.

First of all, I am grateful to Armin Schmutzler, my thesis advisor, for his guidance, support, and criticism. Collaborating with him on the fields of industrial organization and experimental economics was inspiring and fascinating. Moreover, I am grateful to Urs Fischbacher for co-supervising this dissertation.

Further, I am indebted to former and present chair's colleagues: Stefan Bühler, Donja Darai, Dennis Gärtner, Silvia Grätz, Daniel Halbheer, Adrian Müller, Nick Netzer, and Christian Stoff.

I would further like to sincerely thank my girlfriend Rocio for her love, support, and patience.

Finally, my special and deep thank goes to my family. I would like to thank my brother Leonardo whom I have always taken as an example. My emotional thank goes to my parents for allowing me to always count on their full support and encouragement. This dissertation is dedicated to my family.

Zurich, October 2008 Dario Sacco

Introduction

This dissertation deals with a topical issue in the fields of industrial organization and growth theory: The relation between the intensity of competition and process investments. We provide an analysis of this topic through four essays, each with a theoretical and an experimental contribution.

The game-theoretic literature typically uses two-stage oligopoly games to investigate the effect of more intense competition on investment incentives. This effect is generally regarded as ambiguous; depending on the definition of competitive intensity and the particular oligopolistic environment, competition may have different effects on investment.[1] Further, the empirical analysis on the subject is difficult due to the lack of appropriate data, and the related literature also comes to ambiguous conclusions.[2] Therefore, we use laboratory experiments as a complementary research strategy to investigate effects that real-world data would not be able to isolate.

The experimental analysis of Chapter 1 deals with a homogenous Bertrand market where firms invest into cost reduction before product market competition. This market is extremely competitive because only the firm with the lowest marginal costs obtains a positive product-market profit. The second-stage profit is thus a positive function of the own investment and a negative function of the second-highest investment such that the profit is zero when the investments are identical.

The theoretical part of Chapter 1 is not restricted to this particular game. It is a general analysis of all-pay auctions with negative prize externalities. The Bertrand investment game used in the experiment is a special case of the general set-up. In contrast to all-pay auctions with fixed prizes, we consider two sources

[1] Schmutzler (2007) and Vives (2008, forthcoming) synthesize the existing literature. Boone (2000) provides a unifying discussion of different measures of competition.

[2] See, for instance, Gilbert (2006).

of prize endogeneity. First, higher bids (investments) increase the value of the prize (product-market profit); second, the bids of one player have adverse effects on the prize that another player obtains. We show that, for all-pay auctions with bid-dependent prizes, (i) there are pure-strategy equilibria where exactly one player bids a positive amount; (ii) there are symmetric mixed-strategy equilibria where players mix between all strategies up to a cut-off value. (iii) The asymmetric mixed-strategy equilibria identified for the fixed-prize case do not exist;[3] however, an alternative type of asymmetric mixed-strategy equilibrium exists.

The experiment is implemented as a reduced-form version of the Bertrand game where players choose investments and obtain the equilibrium profits corresponding to the resulting product-market subgame.[4] We consider two treatments with two and four players.[5] For both cases, we obtain overinvestment both relative to the symmetric mixed-strategy equilibrium and the social optimum. Subjects choose low investments less than predicted; high investments are chosen more often than predicted, which results in negative profits. Interestingly, the frequency distribution has a lot of mass around the cut-off value of the symmetric mixed-strategy equilibrium, which is also the non-zero investment in the asymmetric pure-strategy equilibrium.

Chapter 2 extends the analysis of Chapter 1 by capturing two notions of more intense competition: Increasing the number of players and switching from Bertrand to Cournot competition. We deal with four different games where two or four firms first choose cost-reducing investments and then compete in a homogenous Cournot or Bertrand market.[6] As predicted, and according with the earlier literature of Isaac and Reynolds (1988, 1992), the experiment shows that an increase in competition in the sense of a larger number of firms leads to lower investments. Rather, switching from Cournot to Bertrand competition yields higher investments, even though theory predicts a negative effect in the four-player case. For both Bertrand and Cournot competition, we obtain over-

[3]For asymmetric mixed-strategy equilibria in the fixed-prize case, see Baye et al. (1996).

[4]This avoid testing optimization in both stages and ensures that potential deviations from the equilibrium investments do not result from anticipations of second-period deviations from the product market equlilibrium. In Chapter 4, we will compare a reduced-form experiment to a two-stage experiment, where subjects take first-stage and second-stage decisions.

[5]However, we do not compare the treatments to identify number effects.

[6]The games are implemented as one-stage experiments, where players only take investment decisions.

investment. However, this overinvestment is more pronounced in the Bertrand case. Thus, the experimental analysis suggests that behavioral effects may imply a more positive effect of competition on investment than a purely theoretic analysis would reveal.

Chapter 3 deals with an alternative but also very common measure of competitive intensity. There, we identify an increase in competition with a reduction in product differentiation. We consider a game where duopolists choose cost-reducing investments in the first stage. In the second stage, they engage in differentiated Cournot competition. We show, that except for firms that are much less efficient than the competitor, there is a U-shaped relation between the intensity of competition and investments. The experiment also provides support for the U-shape, both for symmetric firms and for leaders (which have lower marginal costs ex-ante). Also consistent with predictions, the relation is negative for firms that are lagging behind.[7] However, there are deviations from the equilibrium. In the symmetric case, there is overinvestment. In the asymmetric case, leaders underinvest and laggards overinvest. Interestingly, these deviations mostly reflect best responses to wrong beliefs that players have about the investments of the other subjects. Symmetric players and laggards believe that the competitor invests less than he actually does; rather, leaders believe than the competitor invests more than he actually does.

Finally, Chapter 4 deals with an important issue concerning the experimental design. The experiments discussed in the first three Chapters implement two-stage models as reduced form versions of the original setting. This avoid the chance of an influence of the second stage on the first one, ensuring that equilibrium deviations in stage one do not result from the expectations that subjects have about second-stage outcomes. To test whether the second stage indeed influences first-stage behavior, we implement the game for symmetric players discussed in Chapter 3 as a two-stage experiment, where subjects take investment and quantity decisions. The two-stage experiment does not provide support for the overinvestment obtained in the one-stage experiment. Rather, there is underinvestment, showing that the product market stage has an impact on first-stage investment behavior.

[7] Again, the game is implemented as a one-stage experiment.

References

Baye, M.R., Kovenock, D., de Vries, C.G.: "The All-Pay Auction with Complete Information." *Economic Theory* 8: 291-305 (1996).

Boone, J.: "Competition." *CEPR Discussion Paper*, No. 2636 (2000).

Gilbert, R.J.: "Competition and Innovation." *Journal of Industrial Organization Education* 1(1), 1-23 (2006).

Isaac, R.M., Reynolds, S.S.: "Appropriability and Market Structure in a Stochastic Invention Model." *Quarterly Journal of Economics* 103(4): 647-671 (1988).

Isaac, R.M., Reynolds, S.S.: "Schumpeterian Competition in Experimental Markets." *Journal of Economic Behavior and Organization* 17: 59-100 (1992).

Schmutzler, A.: "The Relation between Competition and Innovation – Why is it such a Mess?" *SOI Working Paper*, No. 716, University of Zurich (2007).

Vives, X.: "Innovation and Competitive Pressure." Forthcoming in *Journal of Industrial Economics* (2008).

Chapter 1

All-Pay Auctions with Negative Prize Externalities

Dario Sacco and Armin Schmutzler

1.1 Introduction

In all-pay auctions, all players cast bids for a prize which only one player obtains. Contrary to ordinary auctions, even the losers have to pay their bids. All-pay auctions have received a lot of attention, as they reflect important aspects of the strategic interaction involved in many different economic activities. For instance, in innovation tournaments, firms' investments influence the probability of winning a patent, the value of which accrues to the winner. In lobbying contests, rival activists can exert effort to achieve the political outcome that is favorable for them. In promotion tournaments, the employees' efforts influence their chances of promotion. Independently of the precise application, the literature usually assumes that the strategic interaction relates exclusively to the chances of obtaining the prize rather than to the ex-post value of the prize, which is assumed to be exogenously fixed.

However, as Baye and Hoppe (2003) point out, there are many important examples where players' activities influence prizes. Specifically, they argue for investment tournaments that a high effort not only increases the chances of obtaining the prize, but also its value. Even though the formulation of their model is general enough to allow for the possibility, these authors do not mention an additional source of prize endogeneity. The efforts of one player may have adverse effects on the prize that another player obtains. For instance, consider a market that is sufficiently competitive that only a firm that is better than the others can earn positive profits. For a particularly stark example, consider a homogenous Bertrand market where firms can invest into cost reduction before product market competition. Then, the firm with the lowest marginal costs obtains the prize, that is, a positive product-market profit, but the size of the prize depends on the investments of the competitors. If the second-best firm has invested almost as much as the winner, the requirement of limit pricing will lead to very low profits for the winner.[1] Thus, investments involve negative externalities not only because they reduce their winning chances, but also because they reduce the prize that the winner will obtain.

For a similar example, suppose the bids in the all-pay auction are specific investments of job candidates (e.g., preparation for job interviews). Then, it is natural to assume that the second-best player's bid (effort) influences the outside options of the prospective employer. Therefore, the prize of the winner, that is, the difference between his wage in the new position and his outside option is likely to depend on the difference between his bid and the second-best bid. In particular, this prize is likely to become small as the second-best bid approaches the winning bid.

This paper therefore analyzes all-pay auctions where the prize (i) is a weakly decreasing function of the second-highest bid such that (ii) the value of the prize is zero when the bids are identical. Finally, we also assume that (iii) the prize is a positive function of the own efforts.

Our first set of contributions is theoretical. We characterize the equilibrium structure of all-pay auctions with negative prize externalities. First, contrary to standard fixed-prize auctions, all-pay auctions with bid-dependent prizes often have pure-strategy equilibria (PSEs) where exactly one player bids a positive amount. However, as there are as many of these (asymmetric) equilibria as there are players, their predictive value is limited. Second, like in the standard case,

[1] In the homogeneous Bertrand case, the equilibrium profit margin of the most efficient firm corresponds to the difference between its costs and those of the second-best firm.

there are typically symmetric mixed-strategy equilibria (MSEs) where players put weight on all strategies up to a cut-off value. Third, the natural analogues of the asymmetric MSEs identified by Baye et al. (1996) for the fixed-prize case do not exist.[2] However, there are asymmetric MSEs where some players mix over all strategies up to a cut-off value and the others put all weight on zero.

The second contribution of the paper is an experimental analysis of a specific all-pay auction with negative prize externalities. We consider parameterized versions of the auction that is derived from the Bertrand investment game; with 2 and 4 players. In both games, players choose investments $Y_i \in \{0, 1, ..., 9\}$. The games have multiple PSEs where one player chooses a positive investment level of 5 and the other player(s) choose 0. In both games, the symmetric MSE has all players mixing between $0, 1, 2, 3, 4$, and 5. The experimental analysis shows that the MSE predicts the percentage of zero investments quite well. However, low, but positive investments are chosen less than predicted; high investments are chosen more often than predicted, which results in negative profits. Interestingly, the frequency distribution has a lot of mass around 5, the non-zero bid in the asymmetric PSE.

As the standard MSE illustrated above is not a fully convincing predictor, we also try to explain the investment behavior through modified objective functions, capturing a "joy of winning" and a "fear of losing". To this end, we extend the profit function of the Bertrand investment game by two parameters: γ and β. The former takes into account the additional benefit from investing more than the others, the latter the additional loss from investing in vain. The MSE obtained in this fashion reflects the investment behavior better, particularly in the 2-player case, but the fit is still imperfect. Summing up, the best interpretation of the evidence is that some players play the symmetric MSE, whereas others speculate that the remaining bidders do not invest, and respond accordingly (like the active bidder in the asymmetric PSE).

Auctions have been discussed extensively in the experimental literature.[3] Experiments on all-pay auctions are comparatively rare, and exclusively concerned with the fixed-prize case. In spite of the differences in the equilibrium structure, our experimental observations are similar to those that are familiar from the

[2] In those equilibria, some players behave as in the symmetric MSE; but other players modify the strategy by not casting any positive, but small bids. Instead, they put all the weight that these strategies receive in the symmetric MSE onto zero.

[3] See Kagel (1995) for a survey.

fixed-prize case. Most closely related is Gneezy and Smorodinsky (2006) who consider symmetric all-pay auctions with 4, 8, and 12 players. Like us, they obtain overbidding that diminishes over time, but remains substantial even in later periods. Also, as in our case, the percentage of very low bids is close to the MSE prediction.[4] Further, one of the six treatments analyzed by Davis and Reilly (1998) corresponds to the fixed-prize all-pay auction.[5] In an experiment with 5 players, the authors observe overbidding that diminishes over time, but does not disappear. Davis and Reilly (1998) also consider the alternative probabilistic set-up that goes back to Tullock (1980).[6] This variant of the all-pay auction has a symmetric PSE. Davis and Reilly (1998) show that overbidding also occurs in the probabilistic case. Earlier experimental evidence on all-pay auctions with fixed prizes is mixed. Millner and Pratt (1989) also observed overbidding, whereas, in the simpler setting of Shogren and Baik (1991) the Nash prediction is fairly accurate. Summing up, even though the equilibrium structure of the all-pay auction with negative prize externalities differs substantially from the fixed-prize case, the experimental observations, in particular, the overbidding phenomenon, are quite similar.

In this paper, we proceed as follows. Section 1.2 contains the general setting with the characterization of the MSE. Section 1.3 introduces the experimental design, including the analysis of the Bertrand investment game. Section 1.4 describes the experimental results, comparing the investment observations in the Bertrand game to the MSE. Section 1.5 discusses alternative MSEs. Section 1.6 concludes.

1.2 The Model

1.2.1 Assumptions

We analyze static games of the following type. Players $i = 1, ..., I$ simultaneously choose bids $b_i \in S = \{0, 1, .., N\} \subset \mathbb{N}^+$. The cost of submitting bid $b_i = n$ is

[4] They also observe positive effects of the number of bidders on revenue and negative effects on average bids, with the former arising only in first periods and the latter only in late periods.

[5] In contrast to Davis and Reilly (1998), the experiment of Gneezy and Smorodinsky (2006) takes the form of a repeated game, where subjects do not rotate among different treatments, playing the same all-pay auction.

[6] In this model, each player wins the prize with probability $b_i / \sum_j b_j$, where b_i is his bid.

k_n such that $k_0 = 0$ and k_n is increasing in n. This includes the standard case that $k_n = n$, but allows for greater generality.[7] Payoffs are given as follows. Let $g(n_i, n_j)$ be a function that is non-decreasing in n_i, non-increasing in n_j and satisfies $g(n_i, n_j) = 0$ whenever $n_i \leq n_j$. Let $b^{(2)}$ be the second-highest bid. Then the payoff of player i is given by

$$f\left(b_i, b^{(2)}\right) = \begin{cases} g(b_i, b^{(2)}) - b_i & \text{if} \quad b_i > b^{(2)} \\ -b_i & \text{if} \quad b_i \leq b^{(2)} \end{cases}. \tag{1.1}$$

Thus, as in a standard all-pay auction, only the highest bidder obtains a positive payoff. However, there is an important twist: The prize for a successful bidder is not fixed. It depends on the winning bid, and on the second-highest bid. The higher the winning bid, the higher the prize; the higher the second-highest bid, the lower the prize. In the limit, as the difference between the highest and the second-highest bid tends to zero, so does the prize. We further maintain the following assumption.

Assumption 1 $g(n_i, n_j)$ is concave in n_i for $n_i > n_j$, and k_n is convex in n.

Of course, the assumption is consistent with the special case that $k_n = n$.

1.2.2 Asymmetric Pure-Strategy Equilibrium

In the following simple characterization of the asymmetric PSEs of the game, let $b^* = \arg\max_{b_i} (g(b_i, 0) - b_i)$.

Proposition 1 *(i) If there exists a PSE of the game such that at least one player i chooses $b_i > 0$, then $b_i = b^*$, all players $j \neq i$ choose $b_j = 0$, and there is one such equilibrium for each player.*
(ii) Such equilibria exist if and only if

$$\max_{b_j} \; (g(b_j, b^*) - b_j) \leq 0. \tag{1.2}$$

The proof is straightforward: (i) If there is more than one player with non-zero bids, at least one of them must earn negative payoffs. Also, the active player must best-respond to zero. (ii) is a simple statement of the best-response

[7] For instance, we shall apply our framework below to the case that $b_i = n$ is a reduction of marginal costs by n, and k_n is the corresponding strictly convex investment cost.

conditions for the candidate equilibria. Intuitively, condition (1.2) requires that those players who choose $b_j = 0$ do not find it profitable to leapfrog player i, that is, to choose $b_j > b^*$. Assumption 1 works in favor of this condition: Intuitively, with concave prizes and convex costs, earning positive payoffs by overbidding a player who has chosen the best response to 0 becomes increasingly difficult. However, in Section 1.3, we will provide an example where asymmetric PSEs even exist in the boundary case that the prize is linear in the own bid.

In spite of its simplicity, the result is interesting, because it stands in stark contrast with the case of fixed prizes. For deterministic all-pay auctions with continuous strategy spaces, PSEs typically do not exist (Baye et al., 1996). This result carries over to the case of discrete bids, as long as the prize is sufficiently large: With a fixed prize v, a PSE would still require that at most one player chooses $b_i > 0$. The best response condition of player i would require $b^* = 1$ because this is sufficient to overbid the other players. However, $b^* = 1$ would make leapfrogging to $b'_j = 2$ attractive for players with $b_j = 0$, unless $k_2 > v$. More generally, even with bid-dependent prizes, a PSE does not exist if $g(n_i, n_j)$ increases more rapidly in n_i than k_{n_i} near $n_i = n_j = n$.

Essentially, with bid-dependent prizes, it often makes sense to overbid the other players by a sufficiently large amount. This may make it unattractive for losing bidders to leapfrog the winner.

1.2.3 Symmetric Mixed-Strategy Equilibrium

Next, we provide a general characterization of symmetric MSEs. The result implies that such equilibria exist under very general conditions, and it provides an algorithm for calculating them. We use the following definitions.

Definition 1 *For any mixed strategy* $\mathbf{p} = (p_0, ..., p_n)$, $p^{-(n)} \equiv p^{-(n,I-1)}$ *is the probability that the highest bid of* $I - 1$ *players following this strategy is* n.

Next, we define a particularly important class of equilibrium candidates.

Definition 2 *Suppose* $M \in \{1, ..., N\}$. *An* M*-equilibrium is a symmetric MSE where all players put symmetric positive weights on strategies* $0, ..., M$, *and zero weights on all higher strategies.*

Proposition 2 provides a recursive formula for calculating symmetric MSEs for all-pay auctions with bid-dependent prizes. In particular, it provides conditions for the existence of such an equilibrium.

Proposition 2 *Suppose that Assumption 1 holds. (i) An M-equilibrium exists if and only if there exists a sequence* $(q_0, ..., q_{M-1})$ *such that:*

$$q_n = \frac{k_{n+1} - k_n - \sum_{m=0}^{n-1} q_m \left(g(n+1,m) - g(n,m)\right)}{g(n+1,n)}, \tag{1.3}$$

where

$$q_n \geq 0 \text{ for } n \leq M-1, \ \sum_{n=0}^{M-1} q_n < 1; \tag{1.4}$$

and

$$\sum_{n=0}^{M-1} q_n g\left(M+1,n\right) + \left(1 - \sum_{n=0}^{M-1} q_n\right) g\left(M+1,M\right) - k_{M+1} \leq 0. \tag{1.5}$$

For this equilibrium, $p^{-(n)} = q_n$ *for* $n \in \{0, ..., M-1\}$.
(ii) If an M-equilibrium exists, it is the unique symmetric MSE.

Proof. See Appendix. ■

We illustrate the meaning of the result, and its proof for $M = 1$. Then, condition (1.5) becomes

$$q_0 g\left(2,0\right) + \left(1-q_0\right) g\left(2,1\right) - k_2 < 0. \tag{1.6}$$

Condition (1.3) applied to $n = 0$ reads $q_0 = \frac{k_1}{g(1,0)}$; and, therefore, (1.4) merely requires that $g(1,0) - k_1 > 0$. By Proposition 2, the game has a symmetric MSE $(p_0, 1-p_0, 0, ..., 0)$ where $p^{-(0)} = q_0 = \frac{k_1}{g(1,0)}$. This probability is such that players are indifferent between bidding 1 unit or not bidding. Also, (1.6) guarantees that bidding 2 units would lead to negative expected payoffs. Using concavity of g and convexity of the function k_n, choosing $b_i > 2$ is not profitable either. The standard characterization result for MSEs (Mas-Colell et al. 1995, Proposition 8.D.1) therefore yields the result.

1.2.4 Asymmetric Mixed-Strategy Equilibrium

Baye et al. (1996) have shown that, for fixed prizes v and continuous bidding, a symmetric equilibrium like the one just derived is not the only MSE of the all-pay auction. In addition, there are asymmetric equilibria where some players randomize over all strategies below a cut-off value, and all other players randomize in exactly the same fashion over all strategies starting from some lower bound above zero up to the cut-off value, but put all the remaining mass on zero. In the following, we show that natural analogues of such equilibria also exist in our discrete game when the prize is fixed. In our more general setting, however, all these equilibria disappear. Instead, there is another type of MSE where some of the players put all mass on zero.

Fixed Prizes

In the degenerate case that the prize v is fixed, we show that there are also many asymmetric MSEs similar to those identified by Baye et al. (1996). To formulate this result, define $P_n = p_0 + ... + p_n$.

Proposition 3 *Suppose the prize is fixed, that is,* $g(n_i, n_j) = v$ *for some suitable constant* $v > 0$ *if and only* $n_i > n_j$*. Suppose there are* $I \geq 3$ *players. Define* $n = M$ *to be the maximal bid such that* $v > k_n$*. Suppose* $J \in \{2, ..., I-1\}$, $r \leq M$*. Then there exist MSEs such that*
(i) J *players choose* $(p_0, ..., p_M, 0, ..., 0)$;
(ii) $I - J$ *players choose* $(P_r, 0, ..., 0, p_{r+1}, ..., p_M, 0, ..., 0)$;
(iii) $P_{n-1} = \left(\frac{k_n}{v}\right)^{1/(I-1)}$ *for* $n \in \{r, ..., M-1\}$;
(iv) $P_{n-1} = \left(\frac{k_n}{v\left(\frac{k_r}{v}\right)^{(I-J)/(I-1)}}\right)^{1/(J-1)}$ *for* $n \in \{1, ..., r-1\}$;
(v) $P_M = 1$.

Proof. See Appendix. ■

To illustrate the proposition, suppose $I = 4$, $M = 3$. Then, the proposition says that there are four types of asymmetric equilibria, which differ with respect to the number of players who are not mixing over all strategies (1 or 2) and the minimal non-zero strategy played by those players (2 or 3).[8]

[8] The condition that $n = M$ be maximal with the property that $v > k_n$ is easily seen to be necessary; for instance, when $M = 2$, there are no equilibria with some bidders randomizing over $0, 1$, and 2, and the remaining bidders randomizing over 0 and 2.

Endogenous Prizes

The next result rules out the possibility that equilibria as derived in Proposition 3 exist when prizes are strictly decreasing in competitor bids. Thus, the equilibrium properties of all-pay auctions with negative prize externalities are dramatically different from those of all-pay auctions with fixed prizes.

Proposition 4 *Suppose $g(n_i, n_j)$ is strictly decreasing in n_j for $n_i > n_j$. Then, there can be no equilibrium such that there exists an $r \geq 2$ such that:*
(i) At least one player chooses $\mathbf{p}$ with positive weights p_0 and p_r;
(ii) At least one player chooses $\widetilde{\mathbf{p}}$ with positive weights $\widetilde{p}_0$ and $\widetilde{p}_r$ such that $\widetilde{p}_0 > p_0$, but $\widetilde{p}_1 = 0$,..., $\widetilde{p}_{r-1} = 0$;
(iii) $\sum_{n=0}^{r-1} p_r = \sum_{n=0}^{r-1} \widetilde{p}_r$.

Proof. See Appendix. ■

This immediately rules out equilibria as in Proposition 3. The scope for asymmetric equilibria is further limited by the following result.

Proposition 5 *There can be no equilibrium such that there exists $r \geq 1$, where $(p_0, ..., p_r) \neq (\widetilde{p}_0, ..., \widetilde{p}_r)$; $p_n > 0$ and $\widetilde{p}_n > 0$ for all $n \in \{0, ..., r\}$.*

Proof. Suppose $s \leq r$ is minimal such that $p_s \neq \widetilde{p}_s$. Then,

$$\sum_{n=0}^{s} p^{-(s)} g\left(s, 0\right) \neq \sum_{n=0}^{s} \widetilde{p}^{-(s)} g\left(s, 0\right), \tag{1.7}$$

contradicting the requirement that both players are indifferent between playing s and 0. ■

Note that this result also holds in the case of fixed prizes.

However, there is one class of asymmetric MSE that does exist. In these equilibria, some players mix over all strategies up to some value M. The remaining players all choose 0.

Proposition 6 *Suppose $I \geq 3$. Then, for every $J \in \{2, ..., I-1\}$, there exist equilibria such that:*
(i) J players randomize over strategies $0, 1, ..., M$, such that $p^{-(n,J-1)} = q_n$ for $n \in \{0, ..., M-1\}$, where q_n is defined as in (1.3) to (1.5);
(ii) The remaining players put all weight on 0.

Proof. See Appendix. ■

In spite of the similarities in the strategies of the J active bidders with those played in the symmetric MSE, there is a crucial difference: As there are some players who put all weight on zero, q^n (for $n > 0$) is the highest remaining bid. The intuition for the result is that, if the J active bidders (who face $J-1$ active bidders and $I-J$ bidders who always bid 0) obtain zero expected profits for all positive bids, the $I-J$ passive bidders (who face J active bidders and $I-J-1$ bidders who always bid 0) must obtain negative expected profits.

1.3 The Experiment

1.3.1 The Bertrand Investment Game

In the following, we will show that a simple two-stage game can be reduced to an all-pay auction with negative prize externalities. In this Bertrand investment game (BIG), all firms $i = 1, ..., I$ are identical ex-ante with constant marginal costs $c > 0$. In the first stage, firms simultaneously choose investments $Y_i \in [0, c)$, resulting in marginal costs $c_i = c - Y_i$.[9] Investment costs are kY_i^2, where $k > 0$. In the second stage, firms compete in the product market as Bertrand competitors; with a demand function $D(p) = a - p$. Let $c_{-i}^m = \min_{j \neq i} c_j$, and denote the monopoly prices and payoffs (gross of investment costs) associated with marginal costs c_i as $p^M(c_i)$ and $\pi^M(c_i)$, respectively. It is well known that gross payoffs of the most efficient firm are

$$\pi_i(c_1, ..., c_I, \alpha) = \begin{cases} (c_{-i}^m - c_i)D(c_{-i}^m), & \text{if } c_{-i}^m \leq p^M(c_i) \\ \pi^M(c_i), & \text{if } c_{-i}^m \geq p^M(c_i) \end{cases}. \tag{1.8}$$

Intuitively, if efficiency differences are sufficiently small that the second-most efficient firm has costs below the monopoly price of the most efficient firm, this firm undercuts the competitors marginally, so that it obtains (approximately) a demand of $D(c_{-i}^m)$ and a markup corresponding to the cost differential; otherwise, it sets the monopoly price. We assume that the efficiency differences are so small that no firm can earn the monopoly profit. Then, defining $Y^{(2)} = \max_{j \neq i} Y_j$, the

[9] Even though we restrict the agents to finite choice sets in the experiment, the theoretical analysis is much more transparent if the choice set is a continuum.

net payoff of firm i is given by

$$\Pi_i(Y_1,...,Y_I) = \begin{cases} (Y_i - Y^{(2)})D(c - Y^{(2)}) - kY_i^2, & \text{if } Y_i > Y^{(2)} \\ -kY_i^2, & \text{if } Y_i \leq Y^{(2)} \end{cases}. \tag{1.9}$$

Hence, with $g(n_i, n_j) = (n_i - n_j)D(c - n_j)$, the game corresponds exactly to our general set-up. Even though this is a two-stage game, by assuming that players play the Nash equilibrium in stage two, we can reduce the game to the first stage. The one-stage game obtained in this fashion corresponds to an all-pay auction with negative prize externalities.

It is straightforward to calculate the equilibria for the BIG. First, as already suggested for the general case in Proposition 1, the game has multiple asymmetric PSEs. Define $\alpha \equiv a - c$.

Proposition 7 *For $k > \frac{1}{2}$, there are multiple asymmetric PSEs with one firm investing $Y_i = \frac{\alpha}{2k}$ and firms $j \neq i$ investing $Y_j = 0$.*

Proof. If firms $j \neq i$ invest $Y_j = 0$, then the best response of firm i is $Y_i = \frac{\alpha}{2k}$ for any $k > 0$. If firm i invests $Y_i = \frac{\alpha}{2k}$, then the best response of the other firms is $Y_j = 0$ for $k > \frac{1}{2}$. ■

Intuitively, if more than one firm invests, then at least one firm obtains zero product market payoffs and therefore negative net payoffs; deviation is therefore profitable.

The BIG also has a symmetric MSE under very general conditions. We calculate this equilibrium in the Appendix.

1.3.2 Experimental Design and Procedures

The experimental design reflects the two-stage investment game which, as mentioned above, can be reduced to an all-pay auction with negative prize externalities, assigning the payoffs of the respective product market game to each investment vector. Apart from making the game more transparent to the experimental subjects, this design feature highlights the nature of the game as an all-pay auction, focusing attention on bidding (investment) rather than on behavior in the product market. This guarantees that deviations do not result from speculations about non-equilibrium behavior in the product market.[10]

[10] For instance, Dufwenberg and Gneezy (2000) have shown that experimental subjects tend to choose prices above marginal costs in symmetric Bertrand games. If subjects anticipate this, the investment incentives will differ from a situation with marginal-costs pricing.

Our two sessions concern two examples of the BIG. We ran a two-player (BIG2) and a four-player treatment (BIG4). The parameter values were $\alpha = 30$ and $k = 3$ for BIG2; $\alpha = 20$ and $k = 2$ for BIG4.[11] We restricted investment choice sets to $Y_i \in \{0, 1, ..., 9\}$ in both cases. Applying the results obtained above, the following holds.

Observation 1 *For BIG2 and BIG4, there are asymmetric PSEs, each with one player investing* 5 *and the other player(s) investing* 0*.*

Coordination on such equilibria is obviously problematic. The MSE is potentially more appealing as a predictor.

Observation 2 (i) *For BIG2, there is a symmetric MSE given by*

$$\left(p_0^{BIG2}, ..., p_9^{BIG2}\right) = (0.1, 0.193, 0.187, 0.182, 0.176, 0.160, 0, 0, 0, 0)\,. \tag{1.10}$$

(ii) *For BIG4, there is a symmetric MSE given by*

$$\left(p_0^{BIG4}, ..., p_9^{BIG4}\right) = (0.464, 0.198, 0.116, 0.086, 0.069, 0.067, 0, 0, 0, 0)\,. \tag{1.11}$$

Hence, in both cases, players randomize over all strategies up to and including 5, the non-zero bid arising in the asymmetric PSE. (i) follows directly from Corollary 1 in the Appendix, because $p_i = q_i$ with two players. As to (ii), Corollary 1 yields

$$(q_0, ..., q_9) = (0.1, 0.190, 0.182, 0.174, 0.167, 0.187, 0, 0, 0, 0)\,, \tag{1.12}$$

from which we obtain

$$p_0^{BIG4} = (q_0)^{1/3} = (0.1)^{1/3} = 0.464. \tag{1.13}$$

The probability $p_1^{BIG4} = 0.198$ follows from

$$q_1 = 3\left(p_0^{BIG4}\right)^2 p_1^{BIG4} + 3\left(p_1^{BIG4}\right)^2 p_0^{BIG4} + \left(p_1^{BIG4}\right)^3 = 0.190. \tag{1.14}$$

Recursively, the other probabilities are obtained.

We note the following immediate implication of Observation 2.

[11] Because BIG2 and BIG4 also differ with respect to α and k, the treatments cannot be compared to identify number effects (see Sacco and Schmutzler, 2008, for a discussion of number effects in investment games).

Observation 3 (i) *For BIG2, the expected investment is* 2.62. (ii) *For BIG4, the expected investment is* 1.30.

The experiments were conducted in February and June 2006 at the University of Zurich. The participants were undergraduate students from various disciplines. Each treatment was run for 20 periods. There were 34 subjects in BIG2 and 36 in BIG4. This led to a total of 1400 investment observations. No subject participated in both sessions. The participants were randomly matched into groups of size 2 or 4 after each period (Stranger design).[12] At the end of each period, subjects were informed about the investment level of the other group member(s) and their own net payoff for that period. All participants received an initial endowment of CHF 35 (≈EUR 22) under BIG2 and CHF 45 (≈EUR 28) under BIG4. Average earnings including the endowment were CHF 32 (≈EUR 20) for BIG2 and CHF 38 (≈EUR 24) for BIG4. Sessions lasted about 90 minutes each. The experiment was programmed and conducted with the software z-Tree (Fischbacher, 2007).

1.4 Experimental Results

1.4.1 The 2-Player Case

Our first observations concern the relation between the symmetric MSE and realized mean investments.

Result 1 *Under BIG2, mean investments are higher than in the symmetric MSE.*

Figure 1.1 reveals that the mean investment level exceeds the equilibrium investment level of 2.62 throughout the 20 periods. A regression over a constant and a Wilcoxon rank sum test show high significance ($p < 0.01$) when considering the difference between predicted and observed investments over all periods. This still holds when taking into account either the last ten or the last five periods. That is, there is no convergence to the Nash equilibrium, even though the investments in the first ten periods are significantly higher than those in the last

[12] The subjects thus take their decisions based on one-shot considerations.

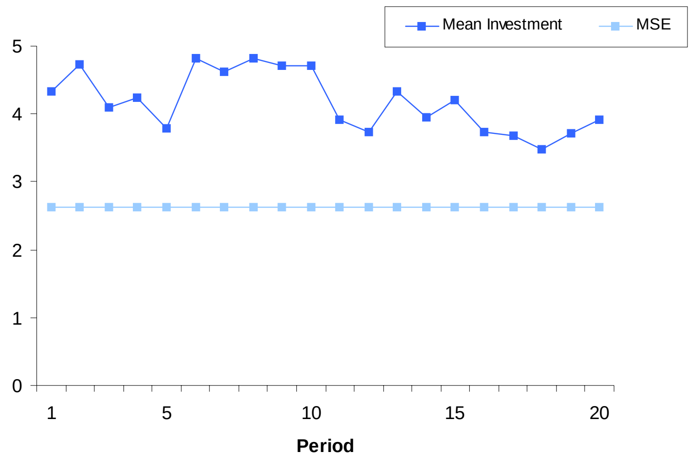

Figure 1.1: Mean investment for BIG2.

ten periods (Wilcoxon rank sum test, $p = 0.016$).[13]

A further interesting aspect concerns the investment distribution. The properties of this distribution over all periods are summarized in Result 2.

Result 2 *Under BIG2, (i) the frequency distribution exhibits a global maximum at 5. (ii) There is a local maximum at 0. (iii) A substantial fraction of the subjects chooses strategies that are not part of the symmetric MSE, that is, invests more than 5.*

Figure 1.2 shows that (i) the investment level of 5 is played in 24% of the cases. (ii) The investment level of 0 is chosen in 15% of the cases. (iii) In 28% of the cases a strategy that is not part of the symmetric MSE is played. We see that the observed investment levels are higher than predicted. Except for the investment level of 0, low investments are chosen less than predicted; high investments more often than predicted.

Qualitatively, the properties summarized in Result 2 also hold in most individual periods, not just in the aggregate.[14]

[13] Gneezy and Smorodinsky (2006) report qualitatively similar results for the symmetric all-pay auction. As described in the introduction, however, there are important differences between the structure of the Bertrand investment game and the all-pay auction.

[14] (i) In 19 periods the investment distribution exhibits a global maximum at 4 or 5. (ii) In 15 periods there is a local maximum at 0. (iii) The fraction of subjects investing more than 5 lies between 15% and 35% per period.

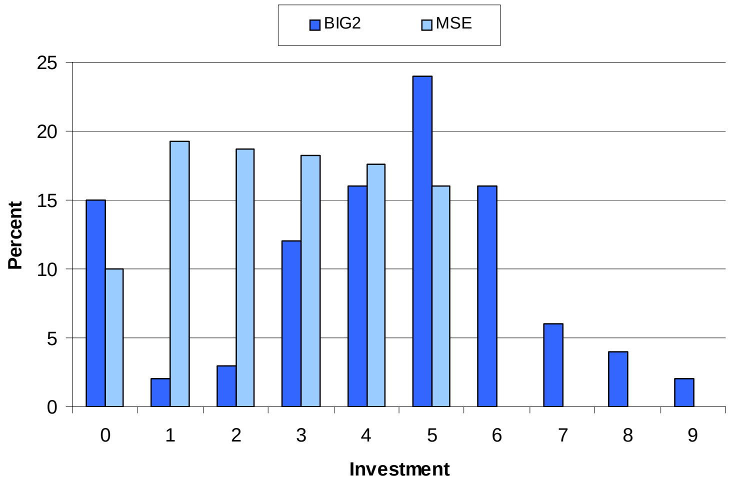

Figure 1.2: Investment distribution for BIG2.

Interestingly, the heterogeneity of investments represents differences in individual investment propensities as much as heterogeneity in investments across time. Table 1.1 shows that the distribution of the mean investments per subject displays similar heterogeneity as the overall distribution of investments.[15] However, the two frequency distributions have qualitatively different features. Specifically, the former has a single global maximum in $[4, 5)$, whereas the latter has a local maximum in 0 apart from the global maximum in 5.

Interval	$[0, 1)$	$[1, 2)$	$[2, 3)$	$[3, 4)$	$[4, 5)$	$[5, 6)$	$[6, 7)$	$[7, 9]$
Frequency	1	1	6	6	11	6	2	1

Table 1.1: Subject distribution for BIG2.

To show how player heterogeneity translates into net payoff differences, we first consider the relation between mean investments and mean losses. Figure 1.3 reveals that there is a clear positive relation.[16] This is closely related to the evolution of the mean net payoff over time. Figure 1.4 shows that the mean net payoff is negative in all periods, even towards the end of the game. Over all periods and subjects, the ratio between total bids (investment costs) and the prize (gross payoffs) is 1.56. The ratio in the first ten periods is higher than

[15] Decomposing the variance into the variance of the average investments of players and the variances of individual players' investments shows that 39% come from the former source.

[16] The regression analysis shows an R^2 of 0.77.

in the last ten periods (1.85 > 1.35). While still substantial, these values are considerably lower than those reported by Gneezy and Smorodinsky (2006) for the case of fixed prizes. There, depending on the treatment, total bids where still 2-3 times higher than the prize in the last period.

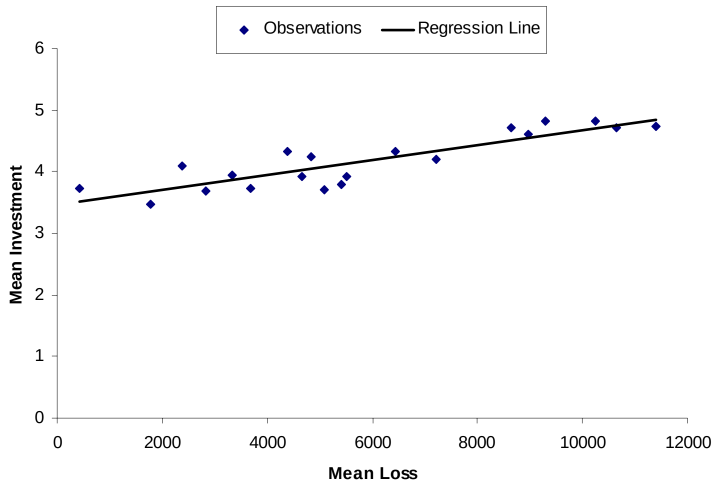

Figure 1.3: The relation between mean investments and losses for BIG2.

1.4.2 The 4-Player Case

The analysis of the 4-player case leads to similar results as in the 2-player case, confirming the overinvestment behavior. We start with the comparison of predicted and observed mean investments.

Result 3 *Under BIG4, mean investments are higher than in the symmetric MSE.*

Figure 1.5 reveals that the mean investment level lies above the equilibrium investment level of 1.30 throughout the 20 periods. Note, however, that there is a downward tendency. The investments in the first ten periods are significantly higher than those in the last ten periods (Wilcoxon rank sum test, $p = 0.018$). Even in the final periods, investments stay above the equilibrium investment, though there is no significant difference for the last 5 periods (Wilcoxon rank sum test, $p = 0.116$).

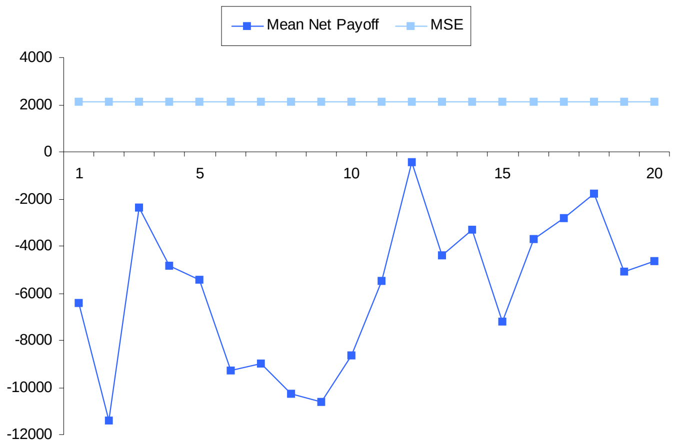

Figure 1.4: Mean net payoff for BIG2.

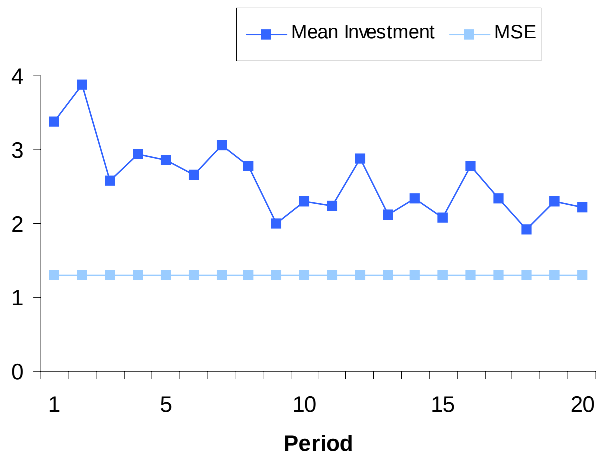

Figure 1.5: Mean investment for BIG4.

Next, we deal with player heterogeneity. The properties of the investment distribution over all periods are summarized in Result 4.

Result 4 *Under BIG4, (i) the frequency distribution exhibits a global maximum at 0. (ii) There is a local maximum at 6. (iii) A substantial fraction of the subjects chooses strategies that are not part of the symmetric MSE, that is, invests more than 5.*

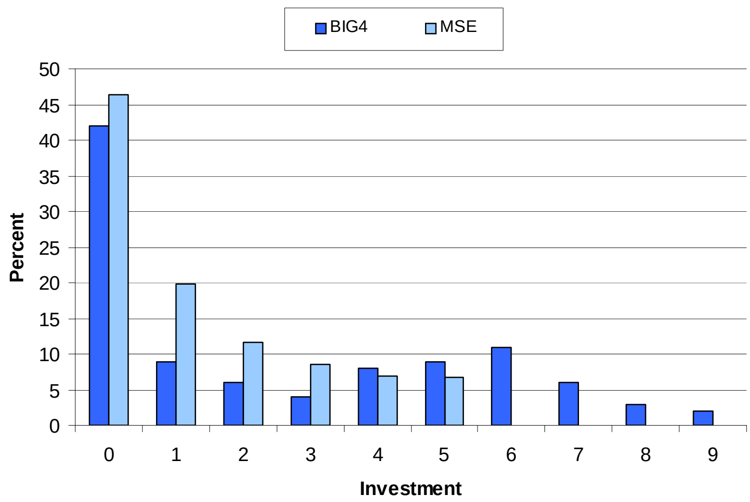

Figure 1.6: Investment distribution for BIG4.

Figure 1.6 shows that (i) the investment level of 0 is played in 42% of the cases. (ii) The investment level of 6 is chosen in 11% of the cases. (iii) In 22% of the cases a strategy that is not part of the symmetric MSE is played. Again, there is overinvestment. Nevertheless, one aspect of the MSE is well reflected in behavior, namely the fact that the investment level of 0 is chosen in almost half of the cases.

The general patterns shown in Result 4 also hold in most individual periods.[17]

Table 1.2 shows that, as in BIG2, the distribution of investments reflects player heterogeneity to a large extent. However, contrary to BIG2, the majority of players now chooses very low average investments, with the mode in $[0, 1)$.

[17] Specifically, (i) in all periods except the first one, the largest fraction of subjects chooses zero. (ii) In 14 periods, there is a local maximum at 5 or 6. (iii) The fraction of subjects investing more than 5 lies between 12% and 32% per period.

10 of the 36 players invest at most one unit on average. Similarly, 10 of the 36 players invest between 4 and 6 units on average.[18]

Interval	$[0,1)$	$[1,2)$	$[2,3)$	$[3,4)$	$[4,5)$	$[5,6)$	$[6,7)$	$[7,9]$
Frequency	10	6	6	3	4	6	1	0

Table 1.2: Subject distribution for BIG4.

Finally, we consider the effect of overinvestment on net payoffs. Figure 1.7 plots mean investments against mean losses. A clear positive relation emerges ($R^2 = 0.87$). The mean net payoffs over the 20 periods are shown in Figure 1.8. The mean net payoff is negative in all periods, implying that the overinvestment is not profitable. Over all periods and subjects, the ratio between bids and prizes is 1.92. Again, the ratio in the first ten periods is higher than in the last ten periods ($2.12 > 1.75$).

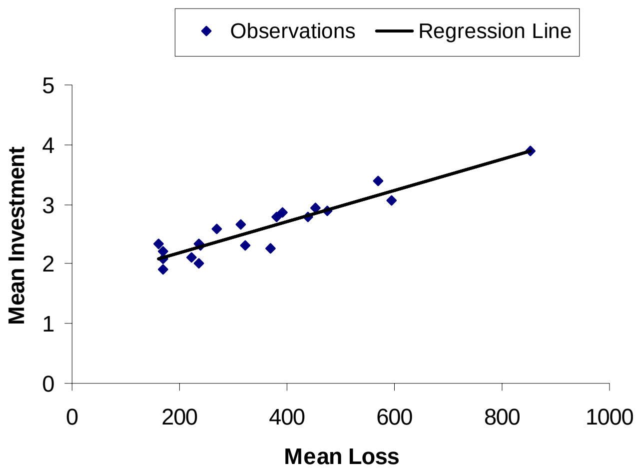

Figure 1.7: The relation between mean investments and losses for BIG4.

Both for BIG2 and BIG4, we have seen that, apart from zero investments, the symmetric MSE discussed above is not a perfect predictor for the observed investment behavior. BIG4 also has asymmetric MSEs (see Proposition 6) where some players put all weight on zero. This does not improve the fit, as this would

[18] The variance's decomposition shows that 48.5% comes from the mean investments.

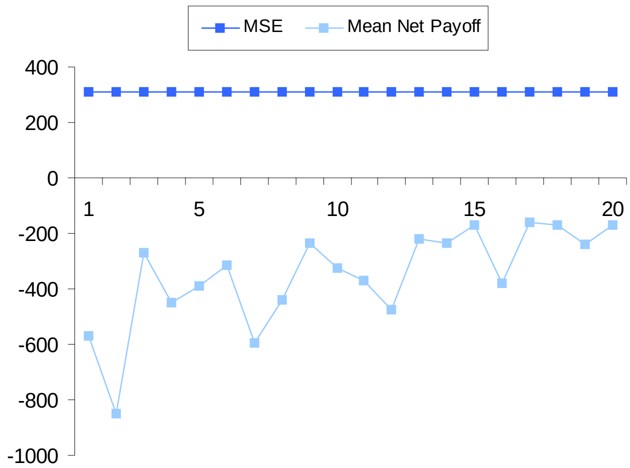

Figure 1.8: Mean net payoff for BIG4.

lead to more weight on 0, rather than on 5. For instance, if $J = 2$, the expected frequencies are given by

$$\left(\hat{p}_0^{BIG4}, ..., \hat{p}_9^{BIG4}\right) = (0.55, 0.095, 0.091, 0.087, 0.083, 0.094, 0, 0, 0, 0)\,. \tag{1.15}$$

The next section discusses MSEs based on alternative objective functions which shall help us to understand the investment behavior better.

1.5 Alternative Objective Functions

For the Bertrand game, we now consider the following modified objective function. The net payoff of firm i given in (1.9) is replaced by

$$\tilde{\Pi}_i(Y_1, ..., Y_I) = \begin{cases} (Y_i - Y^{(2)})D(c - Y^{(2)}) - kY_i^2 + \gamma, & \text{if } Y_i > Y^{(2)} \\ -kY_i^2 - \beta, & \text{if } Y_i \leq Y^{(2)} \wedge Y_i \neq 0 \end{cases}, \tag{1.16}$$

where $\gamma > 0$ and $\beta > 0$.

(1.16) captures the idea that one may derive utility from winning the auction (captured by the parameter γ), and disutility from bidding a positive amount in vain (captured by the parameter β). As we intend to explain overinvestment, we consider parameterizations where $\gamma > \beta$. Subjects might overinvest because they focus on winning on the investment race, neglecting investment costs. In the following, we illustrate the symmetric MSEs of this modified game for two parameterizations. We start with $\gamma = 100$, $\beta = 20$. For BIG2, the investments are shown in Figure 1.9.

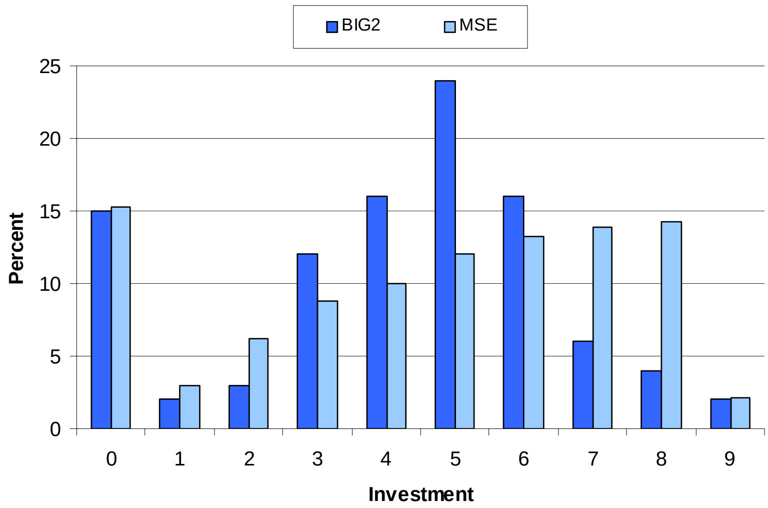

Figure 1.9: Investment distribution for BIG2 $(\gamma = 100, \beta = 20)$.

We see that the predicted zero investments essentially coincide with the observed ones. Further, in contrast to the symmetric MSE of the previous section, the frequency distribution corresponding to the symmetric MSE of the modified game also has two maxima. In spite of this great advantage, the fit is far from perfect: The symmetric MSE has too much mass on very high investments, and it fails to predict the observed global maximum at 5.

The investments for $\gamma = 50$ and $\beta = 20$ are shown in Figure 1.10. The lower value of the γ-parameter implies that the equilibrium does not overpredict high values as much as in the case reflected in Figure 1.9. The symmetric MSE is shifted to the left. The global maximum at 0 is more pronounced (23% instead of 15%), whereas the local maximum is at 6. However, this improvement comes at a cost: The percentage of subjects choosing zero is now predicted less accurately. This trade-off also shows up in other parameterizations. It thus appears that, in spite of the additional degrees of freedom, the modified equilibrium does not capture behavior in a fully satisfactory manner.

In the modified approach just described, subjects obtain some utility from

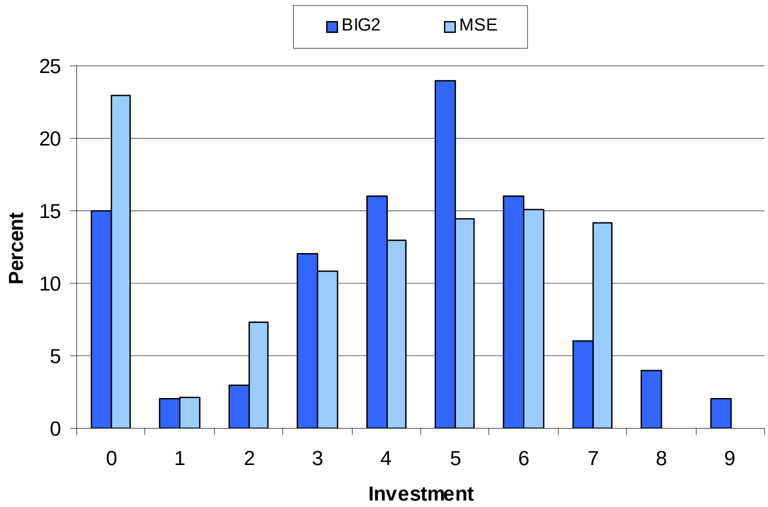

Figure 1.10: Investment distribution for BIG2 $(\gamma = 50, \beta = 20)$.

investing more than the others even if the net payoff is negative.[19] As an alternative, we assume that the additional benefit γ arises only if the net payoff is positive. For the additional loss, the same as above holds. Figure 1.11 shows for $\gamma = 100$ and $\beta = 20$ the frequency distribution in the BIG2. In contrast to Figure 1.9, except for zero investments, the symmetric MSE is more concentrated on the left; the global maximum is at 3. A decrease to $\gamma = 50$ would shift the global maximum from 3 to 0.[20]

Next, consider the 4-player case. In contrast to the 2-player case, the difference between the symmetric MSE with modified payoffs as in (1.16) and the standard symmetric MSE is very small. Figure 1.12 shows the investments for $\gamma = 5$ and $\beta = 1$. In the symmetric MSE, players mix between all investment choices up to 6 instead of 5. Apart from that, there are no consistent differences: Low investments are chosen less than predicted, high investments more often than predicted. Further, a parameter change does not have a large impact. For $\gamma = 2.5$ and $\beta = 1$, the symmetric MSE-distribution is very similar to that of

[19] If the monetary losses from investing more than the others are sufficiently high relative to γ, the net payoff according to (1.16) may be negative.

[20] As a further alternative, we briefly mention the case where the additional benefit γ is given if the net payoff is positive and the additional loss β if the net payoff is negative. The results are qualitatively similar to those illustrated in Figure 1.11. However, a decrease in γ would not shift the global maximum, which is at 3 for both considered parameterizations.

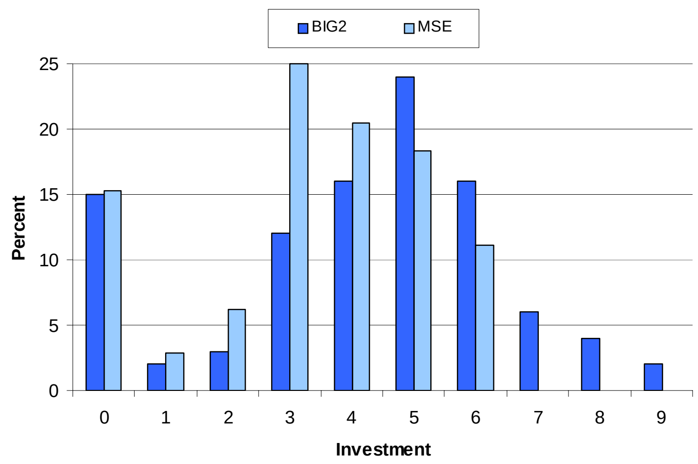

Figure 1.11: Investment distribution for BIG2 $(\gamma = 100, \beta = 20)$.

Figure 1.12.[21]

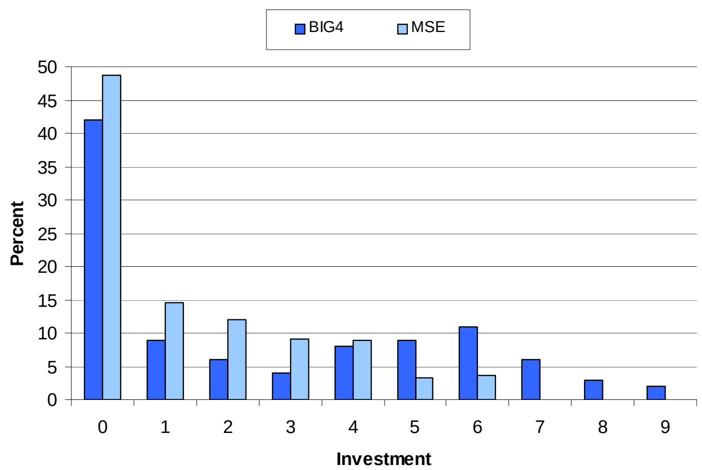

Figure 1.12: Investment distribution for BIG4 $(\gamma = 5, \beta = 1)$.

Summing up, the observed deviations from the symmetric MSE cannot be explained perfectly by a "joy of winning" or "a fear of losing", as proposed

[21] Like for the two-player setting, we also considered the case where the additional benefit γ arises only if the net payoff is positive and another case, where γ is given if the net payoff is positive and β if the net payoff is negative. The MSE does not show remarkable differences with respect to Figure 1.12; we therefore omit additional considerations.

here. One reason may be that the approach does not allow for the asymmetries between players suggested by the experimental observations. It might therefore be useful to consider an alternative approach where the γ and β-parameters are allowed to vary across players, and calculate the Bayesian equilibrium for alternative parameterizations.[22] An alternative, more casual explanation that is also based on player heterogeneity could start from the observation that, at least in BIG2, there is a large concentration of players at 5, which is the best response to 0. This suggests that some players speculate that the opponent abstains from investing, and responds optimally to their own belief.

1.6 Conclusion

We have analyzed all-pay auctions, where the prize is a positive function of the own bid and a negative function of the other players' bids; it is zero when players' bids are identical. That is, the effort of one player has negative externalities on the prize that another player obtains. This negative effect of the own effort on the prize that another bidder gets differentiates our setting from standard all-pay auctions.

We showed that, contrary to the fixed-prize case, the game often has asymmetric PSEs. Like the fixed-prize auction, it has a symmetric MSE. The asymmetric MSEs that loom large in the fixed-prize case analyzed by Baye et al. (1996) do not exist, however.[23] We then provided an experimental analysis that is motivated by a particular example that corresponds to a reduced version of a Bertrand investment game. It turned out that, the symmetric MSE of this game predicts the percentage of zero bids very well. However, like in the fixed-prize case analyzed in earlier experiments (e.g., Gneezy and Smorodinsky, 2006), there is overinvestment, but it is less pronounced.

As the symmetric MSE resulting from the Bertrand investment game does not predict the investment behavior well, we considered alternative payoff functions. We extended the analysis to account for "joy of winning" and "fear of losing". For the 2-player setting, the symmetric MSEs obtained in this fashion reflect the investment behavior better, but not perfectly. For the 4-player setting, the

[22]Standard fixed-prize all-pay auctions have been analyzed as Bayesian games by Amann and Leininger (1996).

[23]However, there are alternative asymmetric MSE where some players mix over strategies up to a cut-off value and others always play zero.

symmetric MSEs based on the modified net payoff functions do not lead to substantial improvements.

Acknowledgement We are grateful to Nick Netzer for helpful comments and suggestions.

Appendix

Proof of Proposition 2

(i) First, consider sufficiency. By (1.4),

$$\left(q_0, ..., q_{M-1}, 1 - \sum_{n=0}^{M-1} q_n, 0, ..., 0\right) \tag{1.17}$$

defines a probability distribution. Together with the requirement that $q_n = p^{(n)}$, (1.3) for $n = 0$ guarantees that players are indifferent between strategies 0 and 1. A simple induction argument yields indifference between all strategies $0, 1, ..., M$: Suppose indifference obtains for some $n = m$, that is,

$$\sum_{n=0}^{m-1} q_n g(m, n) - k_m = 0. \tag{1.18}$$

Then,

$$\sum_{n=0}^{m} q_n g(m+1, n) - k_{m+1} = \sum_{n=0}^{m-1} q_n g(m, n) - k_m +$$

$$\sum_{n=0}^{m-1} q_n \left(g(m+1, n) - g(m, n)\right) + q_m g(m+1, n) - (k_{m+1} - k_m) = 0, \tag{1.19}$$

where the last equation follows from (1.3) and (1.18). The left hand side of (1.5) is the expected payoff that a player would obtain by choosing $M+1$ units, when the other players play the proposed equilibrium $(p_0, ..., p_{M-1}, 1 - p_{M-1}, 0, ..., 0)$ such that $p^{-(n)} = q_n$. Concavity of $g(n_i, n_j)$ and convexity of the function k_n imply that choosing arbitrary $n > M$ would lead to negative expected payoffs. By the standard characterization result for the MSE (Mas-Colell et al. 1995, Proposition 8.D.1), an MSE obtains. Necessity is immediate in view of this characterization result.

(ii) We show that (a) there exists no MSE without weight on zero, and (b) no equilibrium with $p_0 > 0$, $p_r > 0$ for some $r > 0$, and $p_s = 0$ for some $s \in \{1, ..., r-1\}$; (c) At most one M-equilibrium can exist.

(a) Let $n > 0$ be minimal in p such that $q_n > 0$. Then the net payoff from choosing n when all other players choose p is $-k_n < 0$.

(b) Let s be minimal such that $p_s = 0$. Hence,

$$\sum_{n=0}^{s-1} q_n g(s-1,n) - k_{s-1} \geq 0 \geq \sum_{n=0}^{s} q_n g(s,n) - k_s = \sum_{n=0}^{s-1} q_n g(s,n) - k_s. \quad (1.20)$$

Therefore,

$$\sum_{n=0}^{s-1} q_n(g(s,n) - g(s-1,n)) - (k_s - k_{s-1}) \leq 0. \quad (1.21)$$

By concavity of g and convexity of k_n, we have

$$\sum_{n=0}^{s-1} q_n(g(s+1,n) - g(s,n)) - (k_{s+1} - k_s) \leq 0. \quad (1.22)$$

Using (1.20) and (1.22),

$$\sum_{n=0}^{s-1} q_n g(s+1,n) - k_{s+1} \leq 0. \quad (1.23)$$

Next, suppose

$$p_s = 0, ..., p_{s+l-1} = 0, \text{where } l = 2, ..., N-s. \quad (1.24)$$

Then,

$$\sum_{n=0}^{s-1} q_n g(s+l,n) - k_{s+l} =$$

$$\sum_{n=0}^{s-1} q_n g(s+l-1,n) - k_{s+l-1} +$$

$$\sum_{n=0}^{s-1} q_n(g(s+l,n) - g(s+l-1,n)) - (k_{s+l} - k_{s+l-1}) \leq 0. \quad (1.25)$$

(1.25) is non-positive by (1.24) and (1.22). Thus, $p_{s+l} = 0$.

(c) Suppose an M-equilibrium exists. Hence,

$$\sum_{n=0}^{M-1} q_n g(M,n) - k_M = 0. \quad (1.26)$$

An L-equilibrium ($L < M$) would require

$$\sum_{n=0}^{L-1} q_n g(M,n) + (1 - \sum_{n=0}^{L-1} q_n) g(M,L) - k_M \leq 0. \tag{1.27}$$

But,

$$(1 - \sum_{n=0}^{L-1} q_n) g(M,L) > \sum_{n=L}^{M-1} q_n g(M,L) > \sum_{n=L}^{M-1} q_n g(M,n). \tag{1.28}$$

Proof of Proposition 3

The J players who mix between all strategies between 0 and M must be indifferent between all these strategies. To see this, note that (iii) and (iv) imply

$$(P_{n-1})^{I-1} v - k_n = 0 \text{ for } n \in \{r, ..., M\}; \tag{1.29}$$

$$(P_r)^{I-J} (P_{n-1})^{J-1} v - k_n = 0 \text{ for } n \in \{1, ..., r-1\}. \tag{1.30}$$

As the left-hand sides of (1.29) and (1.30) are the expected payoffs of the corresponding strategies, the required indifference conditions hold. For $n > M$, expected payoffs are negative because $v > k_M$.
The $I-J$ remaining players must be indifferent between strategies 0 and $r, ..., M$. As strategies $n \in \{r, ..., M\}$ yield expected payoffs $(P_{n-1})^{I-1} v - k_n = 0$, the indifference condition holds. For strategies $n \in \{1, ..., r-1\}$, these players face a lower chance of having submitted the highest bid than those players that randomize over all strategies. Hence, using (1.30), their expected payoff is negative.

Proof of Proposition 4

Let $p^{-(n)}(\widetilde{p}^{-(n)})$ denote the probability that the highest bid of the opponents of a player who chooses $\mathbf{p}$ ($\widetilde{\mathbf{p}}$) is n. We shall show that, violating the requirement that both types of players obtain expected payoffs equal to k_r when they choose $b_i = r$, the following condition holds:

$$\widetilde{p}^{-(0)} g(r,0) + ... + \widetilde{p}^{-(r-1)} g(r, r-1) < p^{-(0)} g(r,0) + ... + p^{-(r-1)} g(r, r-1). \tag{1.31}$$

To see this, first note that (iii) implies

$$p^{-(0)} = \left(\sum_{n=0}^{r-1} p^{-(n)} - \sum_{n=1}^{r-1} p^{-(n)} \right); \tag{1.32}$$

$$\widetilde{p}^{-(0)} = \left(\sum_{n=0}^{r-1} p^{-(n)} - \sum_{n=1}^{r-1} \widetilde{p}^{-(n)} \right). \tag{1.33}$$

Thus,

$$\sum_{n=0}^{r-1} \left(p^{-(n)} - \widetilde{p}^{-(n)}\right) g(r,n) =$$

$$\left(p^{-(0)} - \widetilde{p}^{-(0)}\right) g(r,0) + \sum_{n=1}^{r-1} \left(p^{-(n)} - \widetilde{p}^{-(n)}\right) g(r,n) =$$

$$\left(\sum_{n=1}^{r-1} \widetilde{p}^{-(n)} - \sum_{n=1}^{r-1} p^{-(n)} \right) g(r,0) + \sum_{n=1}^{r-1} \left(p^{-(n)} - \widetilde{p}^{-(n)}\right) g(r,n) =$$

$$\sum_{n=1}^{r-1} \left(p^{-(n)} - \widetilde{p}^{-(n)}\right) \left(g(r,n) - g(r,0)\right) > 0, \tag{1.34}$$

where the last expression holds because $g(n_i, n_j)$ is strictly decreasing in n_j and (i) and (ii) imply $p^{-(n)} < \widetilde{p}^{-(n)}$ for all $n \in \{1, ..., r-1\}$.

Proof of Proposition 6

(i) Following the argument in the proof of Proposition 2, the conditions in (i) for the J active bidders show that these players obtain zero expected profits on strategies $0, 1, ..., M$.

(ii) Let $\hat{p}^{-(n)}$ denote the probability that the highest of the remaining bids for $I - J$ passive bidders is n. Because, compared with an active bidder, each passive bidder faces one more active bidder and one less passive bidder, $\hat{p}^{-(n)}$ stochastically dominates $p^{-(n)}$, that is, there exists an $r \in \{1, ..., M\}$ such that:

$$\hat{p}^{-(n)} < p^{-(n)} \text{ for } n \in \{0, ..., r-1\}; \tag{1.35}$$

$$\hat{p}^{-(n)} > p^{-(n)} \text{ for } n \in \{r, ..., M\}; \tag{1.36}$$

By (1.35),

$$\sum_{n=0}^{s-1} \hat{p}^{-(n)} g(s,n) < \sum_{n=0}^{s-1} p^{-(n)} g(s,n) \ \forall s \in \{0, ..., r\}. \tag{1.37}$$

By (1.35) and (1.36),

$$\sum_{n=0}^{s-1} \hat{p}^{-(n)} g(s,n) - \sum_{n=0}^{r-1} p^{-(n)} g(r,n) =$$

$$\sum_{n=0}^{r-1}\left(\hat{p}^{-(n)}-p^{-(n)}\right)g(s,n)-\sum_{n=r}^{s-1}\left(p^{-(n)}-\hat{p}^{-(n)}\right)g(s,n)<$$

$$g(s,r-1)\sum_{n=0}^{r-1}\left(\hat{p}^{-(n)}-p^{-(n)}\right)-g(s,r)\sum_{n=r}^{s-1}\left(p^{-(n)}-\hat{p}^{-(n)}\right)<0. \tag{1.38}$$

(1.38) holds because

$$g(s,r-1)>g(s,r) \tag{1.39}$$

and

$$\sum_{n=0}^{r-1}\left(\hat{p}^{-(n)}-p^{-(n)}\right)>\sum_{n=r}^{s-1}\left(p^{-(n)}-\hat{p}^{-(n)}\right). \tag{1.40}$$

The Bertrand Investment Game

Proposition 2 immediately allows us to characterize the symmetric MSE as follows.

Corollary 1 *A symmetric MSE of the BIG exists if and only if, for some $M \in \{1,...,N\}$, there exists a sequence $(q_0,...,q_{M-1})$ satisfying*

$$q_n=\frac{k_{n+1}-k_n-\sum_{n=0}^{M-1}q_m\left(\alpha+m\right)}{\left(\alpha+n\right)}, \tag{1.41}$$

where

$$q_n\geq 0 \text{ for } n\leq M-1,\ \sum_{n=0}^{M-1}q_n<1; \tag{1.42}$$

and

$$\sum_{n=0}^{M-1}q_n\left(M-n\right)\left(\alpha+n\right)+\left(1-\sum_{n=0}^{M-1}q_n\right)\left(\alpha+M-1\right)-k_M<0. \tag{1.43}$$

The equilibrium is given as $(p_0,...,p_{M-1},1-p_{M-1},0,...,0)$ such that for $n=0,...,M-1$ q_n is the probability that, given $(p_0,...,p_n)$, the highest of $I-1$ bids is n.

References

Amann, E., Leininger, W.: "Asymmetric All-Pay Auctions with Incomplete Information: The Two-Player Case." *Games and Economic Behavior* 14: 1-18 (1996).

Baye, M.R., Hoppe, H.C.: "The Strategic Equivalence of Rent Seeking, Innovation, and Patent-Race Games." *Games and Economic Behavior* 44: 217-226 (2003).

Baye, M.R., Kovenock, D., de Vries, C.G.: "The All-Pay Auction with Complete Information." *Economic Theory* 8: 291-305 (1996).

Davis, D., Reilly, R.J.: "Do too many Cooks always Spoil the Stew? An Experimental Analysis of Rent-Seeking and the Role of a Strategic Buyer." *Public Choice* 89-115 (1998).

Dufwenberg, M., Gneezy, U.: "Price Competition and Market Concentration: An Experimental Study." *International Journal of Industrial Organization* 18(1): 7-22 (2000).

Fischbacher, U.: "Z-Tree. Toolbox for Readymade Economic Experiments." *Experimental Economics* 10(2), 171-178 (2007).

Gneezy, U., Smorodinsky, R.: "All-Pay Auctions – An Experimental Study." *Journal of Economic Behavior and Organization* 61: 255-275 (2006).

Kagel, J.H.: "*Auctions: A Survey of Experimental Research.*" In: Kagel, J.H., Roth, A.E. (Eds.). The Handbook of Experimental Economics. Princeton University Press: 501-585 (1995).

Mas-Colell, A., Whinston, M.D., Green, J.R.: *Microeconomic Theory.* Oxford University Press (1995).

Millner, E.L., Pratt, M.D.: "An Experimental Investigation of Efficient Rent-Seeking." *Public Choice* 62: 139-151 (1989).

Sacco, D., Schmutzler, A.: "Competition and Innovation: An Experimental Investigation." *SOI Working Paper*, No. 807, University of Zurich (2008).

Shogren, J.F., Baik, K.H.: "Reexamining Efficient Rent-Seeking in Laboratory Markets." *Public Choice* 69: 69-79 (1991).

Tullock, G.: "*Efficient Rent Seeking.*" In: Buchanan, J.M., Tollison, R.D., Tullock, G. (Eds.). Towards a Theory of the Rent Seeking Society. Texas A&M University Press, College Station: 97-112 (1980).

Chapter 2

Competition and Innovation: An Experimental Investigation

Dario Sacco and Armin Schmutzler

2.1 Introduction

Simple two-stage games are often used to derive predictions about the effects of the intensity of competition on cost-reducing investments.[1] The empirical test of these predictions is very difficult, and the literature comes to ambiguous conclusions.[2] Therefore, this paper uses laboratory experiments as a complementary research strategy to explore whether at least the basic strategic effects identified in the theoretical models are present in a laboratory setting.

Specifically, we consider four different games where two or four firms can choose a cost-reducing investment before they engage in Cournot or Bertrand competition. In this fashion, we can explore the effects of increasing competition both by increasing the number of players and by switching from Cournot to Bertrand competition. Thus, we can capture two of the most familiar notions of increasing competition. The predicted effect of competition on investment is unambiguously negative for an increase in the number of firms. For a shift from

[1] Schmutzler (2007) and Vives (2008, forthcoming) synthesize the existing literature.

[2] See Gilbert (2006).

Cournot to Bertrand competition, the effect is mostly negative, except in the duopoly case for some parameter constellations, including one of the treatments we considered.

The experiments fully confirm the negative number effects.[3] For a switch from Cournot to Bertrand competition, however, the observed effect is always positive, even when the predicted effect is negative. This observation relates to how players deviate from the Nash equilibrium. In both cases, there is overinvestment. However, this overinvestment is more pronounced in the Bertrand case, so that there may be a positive effect of switching from Cournot to Bertrand even when theory predicts a negative effect.

Obviously, a simple set of experiments cannot resolve the century-old debate about the effects of competition on investment. First of all, there are too many conceptual ambiguities at the theoretical levels. Even the definition of increasing intensity of competition is contentious, some insightful attempts to structure the debate notwithstanding.[4] Second, even if one settles for a specific notion of increasing competition in two-stage games, there is a bewildering variety of models to investigate the issue.[5] Third, of course, one can go beyond the two-sage setting and investigate more complicated dynamic models.[6] Finally, one may worry about the external validity of the laboratory setting as a means of testing predictions about the long-term strategic decisions of managers in (potentially large) firms.

In spite of all these cautionary remarks, we believe that the subsequent analysis leads to one important insight: Our laboratory analysis suggests that behavioral effects may imply a more positive effect of competition on investment than

[3] Importantly, note that our analysis is distinct from the more familiar analysis of number effects in oligopolies (Huck et al., 2004; Orzen, 2008, forthcoming). This literature deals with the effects on prices and quantities rather than on investments.

[4] Boone (2000) shows that many different measures of competition share the common property that increasing competition can be associated with a higher ratio of the profits between more efficient and less efficient firms.

[5] Vives (2008, forthcoming) provides a unifying discussion of two-stage games, with the extent of product differentation as an inverse measure of competition. Schmutzler (2007) extends the discussion to other measures of competition.

[6] For instance, Lee and Wilde (1980) identify a positive effect of the number of firms on investment per firm in a Bertrand setting, whereas Delbono and Denicolò (1991) find a negative effect, even on total investment, in the Cournot case. In a stochastic patent race preceding product market competition, Delbono and Denicolò (1990) show that investment in the Bertrand case is unambiguously higher than in the Cournot case. Bester and Petrakis (1993) show that, with sufficiently large horizontal product differentiation, the innovation incentive is higher under Cournot competition than under Bertrand competition.

a purely theoretic analysis would reveal. Future work will have to show how robust these effects are in the lab. More importantly, perhaps, it will have to show whether the effect is also present in the field.

There are only few experimental studies which directly deal with the linkage between intensity of competition and R&D investments. Isaac and Reynolds (1988, 1992) consider the number effects. They deal with stochastic static and dynamic patent races and show that an increase in the group size lowers investment per firm and raises aggregate investment. We are not aware of experimental papers comparing Cournot to Bertrand competition. In Sacco and Schmutzler (2008), we analyze a two-stage Bertrand game, where investments precede price competition.[7] We show that overinvestment is substantial. However, there, we do not deal with the effects of increasing competition.[8]

The paper is structured as follows. Section 2.2 contains the theoretical framework. Section 2.3 describes the experimental design and results. Section 2.4 concludes.

2.2 The Model

We analyze static two-stage games, where firms $i = 1, ..., I$ first invest in R&D and then compete in the product market. The demand function for the homogenous product is given by $D(p) = a - p$, with $a > 0$. All firms i are identical ex-ante with constant marginal costs $c > 0$. In the first stage, firms simultaneously choose R&D investments $Y_i \in [0, c)$, resulting in marginal costs $c_i = c - Y_i$.[9] The cost of R&D is given by kY_i^2, where $k > 0$. In the second stage, firms simultaneously choose quantities (Cournot) or prices (Bertrand). We refer to the Cournot case as soft competition (SC); to the Bertrand case as intense competition (IC).

[7] Suetens (2005) considers investment games in a Cournot setting. However, she is not concerned with the effects of competition.

[8] The theoretical part of the paper deals more generally with all-pay auctions with negative prize externalities. The Bertrand investment game used in the experiment is a special case of the general set-up.

[9] Even though agents are restricted to finite strategy sets in the experiment, the theoretical analysis is much more transparent if the strategy set is a continuum.

2.2.1 Soft Competition

For SC, backward induction shows that the net payoff function of firm i in the first stage is given by

$$\Pi_i(Y_1, ..., Y_I, \alpha, k) = \left(\frac{\alpha + IY_i - \sum_{i \neq j} Y_j}{I+1} \right)^2 - kY_i^2, \tag{2.1}$$

where $\alpha \equiv a - c$ represents the demand parameter.[10]

The gross payoff of firm i, that is, the first term on the right-hand side of (2.1), depends positively on its own investment and the demand parameter, and negatively on the investments of the other firms. Competition is soft in the sense that even a firm that invests less than the others achieves a positive gross payoff, unless $Y_i \ll Y_j$.

Maximizing (2.1) with respect to Y_i yields

$$\frac{\partial \Pi_i(\cdot)}{\partial Y_i} = \frac{2I(\alpha + IY_i - \sum_{i \neq j} Y_j)}{(I+1)^2} - 2kY_i \equiv 0. \tag{2.2}$$

We assume that the second order condition holds, that is,

$$\frac{\partial^2 \Pi_i(\cdot)}{\partial Y_i^2} = \frac{I^2}{(I+1)^2} - k < 0, \tag{2.3}$$

which is fulfilled for arbitrary $I \geq 2$ if $k > 1$.

The equilibrium follows immediately from (2.2).

Proposition 8 *Under SC, the symmetric pure-strategy Nash equilibrium investment levels are*

$$Y^{SC} = \frac{\alpha I}{k(I+1)^2 - I}. \tag{2.4}$$

By (2.4), equilibrium investments are increasing in the demand parameter α, and decreasing in the cost parameter k and in the number of firms I.

2.2.2 Intense Competition

For IC, backward induction shows that the net payoff function of firm i in the first stage is given by

$$\Pi_i(\cdot) = \begin{cases} (Y_i - Y_{-i}^m) D(c - Y_{-i}^m) - kY_i^2, & \text{if } Y_i > Y_{-i}^m \\ -kY_i^2, & \text{if } Y_i \leq Y_{-i}^m \end{cases}, \tag{2.5}$$

[10] Here and in the following, we assume that $\alpha + IY_i - \sum_{i \neq j} Y_j \geq 0$.

where $Y_{-i}^m = \max_{j \neq i} Y_j$. Competition is intense in the sense that a firm can achieve a positive gross payoff only by investing more than the highest investment of the others. If $Y_i > Y_{-i}^m$, maximizing (2.5) with respect to Y_i gives

$$\frac{\partial \Pi_i(\cdot)}{\partial Y_i} = D(c - Y_j^m) - 2kY_i \equiv 0. \tag{2.6}$$

$Y_i \leq Y_{-i}^m$ can only be a best response if $Y_i = 0$ holds: If firm i does not invest more than all others, it gets a negative net payoff. In such a case the deviation to $Y_i = 0$ is profitable. The pure-strategy equilibrium is thus characterized as follows.

Proposition 9 *(i) Under IC, for $k > \frac{1}{2}$, there are multiple asymmetric pure-strategy equilibria with one firm investing $Y_i^{IC} = \frac{\alpha}{2k}$ and firms $j \neq i$ investing $Y_j^{IC} = 0$. (ii) There are no other pure-strategy equilibria.*

Proof. (i) If firms $j \neq i$ invest $Y_j^{IC} = 0$, then according to (2.6) the best response of firm i is $Y_i^{IC} = \frac{\alpha}{2k}$ for any $k > 0$. If firm i invests $Y_i^{IC} = \frac{\alpha}{2k}$, then the best response of the other firms is $Y_j^{IC} = 0$ for $k > \frac{1}{2}$. That is, firm j does not have an incentive to exceed the investment of firm i by choosing $Y_j^{IC} = \frac{\alpha}{2k} + \Delta$, where $\Delta > 0$. The value $\Delta = \frac{\alpha}{4k^2}$ maximizes $\Pi_j(\cdot)$ which is negative for $k > \frac{1}{2}$. (ii) is immediate. ■

Thus, the average equilibrium investment level is given by

$$\overline{Y}^{IC} = \frac{\alpha}{2kI}, \tag{2.7}$$

which is increasing in the demand parameter, and decreasing in the cost parameter k and in the number of firms I.

It is unlikely that agents can coordinate on one of the asymmetric pure-strategy equilibria, in particular, because only the investor obtains positive payoffs. In the experimental analysis, we therefore refer to the following result of Sacco and Schmutzler (2008).

Proposition 10 *The IC-game has a symmetric mixed-strategy equilibrium, where firms mix between all strategies up to a cut-off level.*

In the companion paper, we also provide an algorithm for calculating this equilibrium.[11]

[11] The game also has asymmetric mixed-strategy equilibria where some firms always play zero and others randomize.

2.2.3 The Effects of Increasing Competition

We now show that, with a small qualification for the comparison between SC and IC, the predicted effects of competition on investment are negative.

Corollary 2 *For a given type of product market competition, SC or IC, the average equilibrium investments are decreasing in I.*

Similarly, comparing (2.4) to (2.7), the following result arises.

Corollary 3 *Suppose that (2.3) holds and $k > \frac{1}{2}$. The average equilibrium investment for SC is higher than the average investment in each asymmetric pure-strategy equilibrium for IC unless $I = 2$ and $k > 2$.*

Though we cannot provide such a result for the mixed-strategy equilibrium at this level of generality, a similar statement holds for the parameters we choose (see 2.3.1).

Thus, except for the caveat for $I = 2$, for both concepts of competitiveness, an increase in competition reduces investment.

2.3 The Experiment

2.3.1 Choosing the Parameters

We conducted four treatments. There were two sessions with two-player groups (SC2 and IC2) and four-player groups (SC4 and IC4), respectively.[12] Further, we chose $\alpha = 30$ and $k = 3$. In the experiments, we restricted the strategy sets to $Y_i \in \{0, 1, ..., 9\}$. It can be shown that the equilibria of the game with the discrete strategy set are $(2, 2)$ for SC2 and $(2, 2, 2, 2)$ for SC4. However, this prediction relies on an extremely mechanical application of the Nash equilibrium. It is straightforward to show that marginal investment incentives are higher for each player in SC2 than in SC4. Economic intuition therefore suggests that the effect of increasing the number of players should be negative.[13] This prediction is obtained if one views the players as playing a continuous game: In the Nash

[12] The results for IC2 are also reported in Sacco and Schmutzler (2008).

[13] Schmutzler (2007) formalizes this intuition. He gives general conditions under which an increase in the number of players (weakly) reduces the investments of players in an investment game. These conditions hold in the example.

equilibrium of the continuous version of SC2, investments are higher than for SC4 ($2.4 > 1.69$).

Under IC, according to Proposition 9, there are asymmetric equilibria, each with one firm investing 5 and the other firm(s) 0. This holds both for the discrete and continuous strategy set. Moreover, according to Sacco and Schmutzler (2008), IC2 has a symmetric mixed-strategy equilibrium (MSE) given by

$$(p_0, ..., p_9) = (0.1, 0.193, 0.187, 0.182, 0.176, 0.160, 0, 0, 0, 0) . \tag{2.8}$$

For IC4, the symmetric MSE is given by

$$(p_0, ..., p_9) = (0.464, 0.2, 0.119, 0.088, 0.071, 0.057, 0, 0, 0, 0) . \tag{2.9}$$

The expected investment level is 2.62 for IC2 and 1.27 for IC4.[14]

2.3.2 Experimental Design and Procedures

The experimental sessions were conducted in June and November 2006 at the University of Zurich. The participants were undergraduate students.[15] To focus on investment choices, we reduced the games to the first stage, that is, to the investment stage. For each investment profile, players earned the unique Nash equilibrium payoffs of the corresponding subgame. Thus, we did not model the product market stage explicitly.[16] This allows us to avoid confusion about the source of possible deviations from the equilibrium in the investment game: Contrary to a two-stage experiment, investment decisions cannot be influenced by speculations about deviations from equilibria in the product-market stage.[17]

We implemented two sessions with IC treatments, and two with SC treatments. In each session there were 20 periods and in two of four sessions 36 subjects.[18] This led to a total of 2760 investment observations. No subject participated in more than one session. The participants were randomly matched

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[14] Note that the expected investment levels are close to the average investments ($\overline{Y}^{IC2} = 2.5$; $\overline{Y}^{IC4} = 1.25$).

[15] We did not exclude any disciplines. We had students of law, engineering, psychology, economics etc.

[16] A similar strategy was pursued in the Cournot investment experiments of Halbheer et al. (2007). Sacco (2008) compares the behavior of subjects in a two-stage experiment with behavior in the corresponding reduced-form game.

[17] Such deviations are known to arise both in the Bertrand case (Dufwenberg and Gneezy, 2000) and in the the Cournot case (Huck et al., 2004, and many others).

[18] In the SC4 and IC2 sessions there were 32 and 34 participants, respectively.

into groups of size two or four after each period. This corresponds to a Stranger design.[19] At the end of each period, subjects were informed about the investment level of the other group member(s) and their own net payoff for that period. In each session, participants received an initial endowment of CHF 35 (≈EUR 22). Average earnings including the endowment were CHF 31 (≈EUR 19) for IC2 and CHF 32.50 (≈EUR 20) for IC4. The amounts for SC2 and SC4 were CHF 49 (≈EUR 31) and CHF 39 (≈EUR 24), respectively. Sessions lasted about 90 minutes each. The experiment was programmed and conducted with the software z-Tree (Fischbacher, 2007).

2.3.3 Results

Based on the results contained in 2.2.3 and 2.3.1, we test the following hypotheses.

Hypothesis 1 Investments are lower in SC4 than in SC2.

Hypothesis 2 Investments are lower in IC4 than in IC2.

Hypothesis 3 (a) Investments are lower in IC4 than in SC4. (b) Investments are higher in IC2 than in SC2.

That is, we first consider the effects of increasing the number of players. The analysis of the SC treatment (Hypothesis 1) precedes that of the IC treatment (Hypothesis 2). Second, for a given number of players, we consider the effects of switching from SC to IC (Hypothesis 3).

Soft Competition

The mean investments over all periods and subjects are 2.59 and 1.83 for SC2 and SC4, respectively. These are slightly above, but very close to the equilibria of the continuous version of the SC game. Hence, in spite of the discrete formulation of the game, the continuous game may provide better predictions than the discrete game, which, to repeat, predicts average investments of 2 in both cases. This point is interesting beyond the specific game.

[19] Observe that through the choice of a Stranger design the experimental analysis is based on one-shot considerations.

Result 5 *Mean investments are higher for SC2 than for SC4.*

Considering all periods, both a regression over a constant and a Wilcoxon rank sum test show that the difference between the two treatments is highly significant ($p < 0.01$). This also holds in the last five periods. That is, the mean investment level under SC2 does not converge to that under SC4.

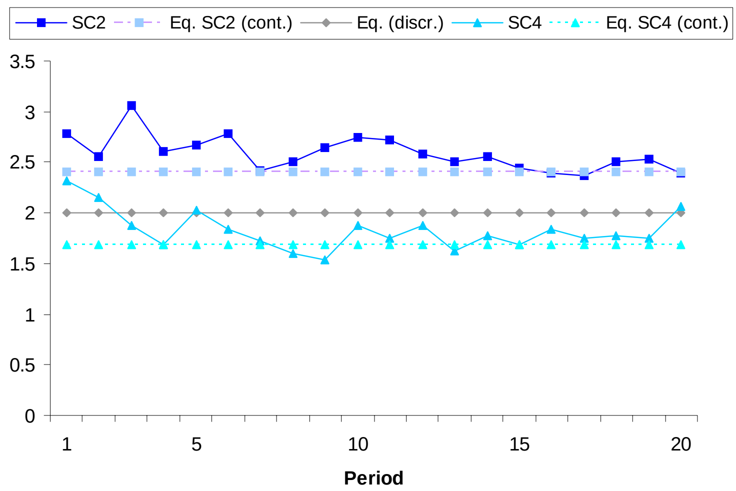

Figure 2.1: Mean investments under SC.

Figure 2.1 reveals that there is overinvestment for SC2 and underinvestment for SC4 if one takes the equilibrium of the discrete game as the benchmark.[20] Relative to the equilibrium of the continuous game, there is overinvestment in both cases. Over all periods, the difference between observed investments and corresponding continuous benchmark is highly significant. However, in the last five periods, the difference is significant only for SC4 ($p = 0.017$).

While the main objective of this subsection was the test of Hypothesis 1, we also note in passing that investments are concentrated around the equilibrium (see Figure 2.2).

Result 6 *For SC2, 77% of the investments over all periods are either 2 or 3. For SC4, 80% of the investments are either 1 or 2.*

[20] In SC2, the difference between investments and Nash equilibrium is highly significant over all periods. This also holds in the last five periods. In SC4, the difference with respect to the prediction is likewise highly significant throughout the 20 periods. Interestingly, this also holds in the last five but not in the first five periods.

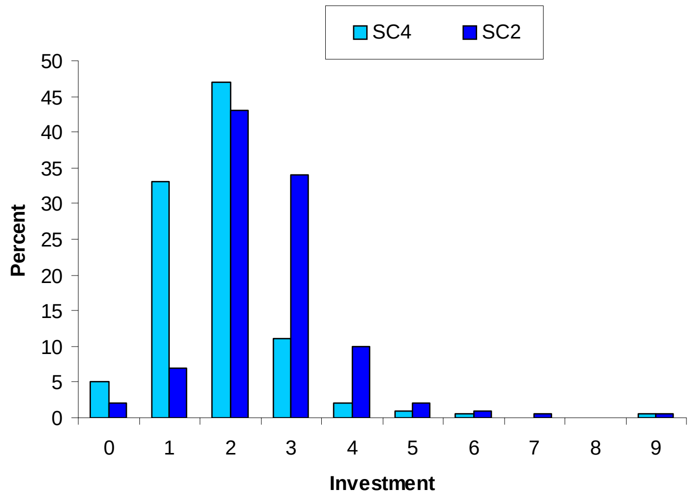

Figure 2.2: Investment distributions under SC.

Also, the concentration around the equilibrium arises in almost every single period.[21]

Finally, the concentration of investments around the equilibrium is also reflected in the average investments of each player.

Interval	$[0,1)$	$[1,2)$	$[2,3)$	$[3,4)$	$[4,5)$	$[5,6)$	$[6,7)$	$[7,8)$	$[8,9]$
SC2	0	1	28	6	1	0	0	0	0
SC4	2	20	9	1	0	0	0	0	0

Table 2.1: Subject distributions under SC.

For each interval of length 1, Table 2.1 gives the number of subjects whose average investment is in the interval. For SC2, 28 of the 36 subjects choose mean investments over the 20 periods between 2 and 3. For SC4, 20 of the 32 subjects have mean investments between 1 and 2.

The observed deviations from the Nash equilibrium are strikingly different from those in standard Cournot oligopoly games where players choose outputs rather than investments. These games are structurally very similar to the reduced version of the investment game, in that they also feature strategic substi-

[21] Under SC2, the investment level of 2 is chosen most often in 17 periods, followed by 3. In the remaining three periods, 3 is the most frequently played investment level, followed by 2. Under SC4, again in 17 periods, 2 is chosen most often, followed by 1. In the other three periods, 1 is played most often, followed by 2.

tutes and negative externalities. Hence, in the Nash equilibrium, players choose more output than under joint-profit maximization. In experiments with few players, subjects collude, that is, choose output levels below the Nash equilibrium and closer to joint-profit maximization. For more players, this result is reversed; output is even higher than predicted in the Nash equilibrium (Huck et al., 2004). Thus, more intense competition leads to less cooperative behavior. For our investment games, this is no longer true, no matter whether one uses the discrete or the continuous game as a benchmark. Relative to the former benchmark, the Huck et al. (2004) results are reversed: Players choose too high levels of the non-cooperative action for SC2, but too low levels for SC4. Relative to the latter benchmark, actions are too high for both SC2 and SC4.

Intense Competition

Next, we consider Hypothesis 2, which is based on the result that the expected investment level in the MSE for IC2 (2.62) is higher than for IC4 (1.27). The experiment provides evidence for this prediction.

Result 7 *Mean investments are higher for IC2 than for IC4.*

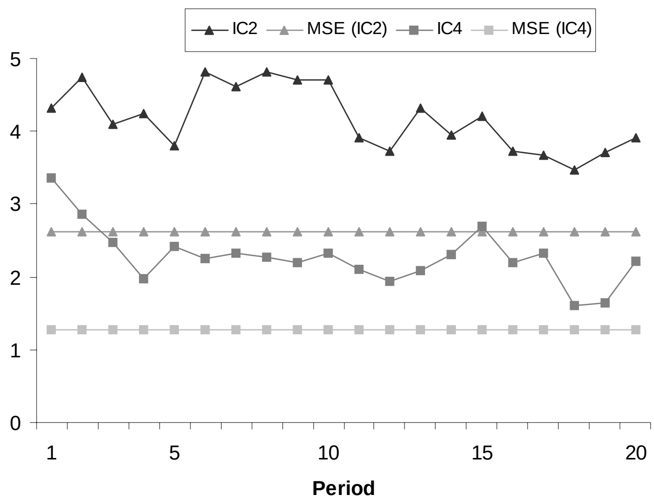

Figure 2.3: Mean investments under IC.

Figure 2.3 reveals that the mean investment level under IC2 does not approach the one under IC4. The difference between the two treatments is highly significant over all periods, and even in the last ten or the last five periods.[22]

Figure 2.3 also shows that, both under IC2 and IC4, the mean investments over the 20 periods always lie above the MSE values of 2.62 and 1.27, respectively. In IC2, the difference between investments and the MSE is highly significant throughout the 20 periods. This still holds in the last ten or the last five periods. That is, there is no convergence to the Nash equilibrium value of 2.62, even though the investments in the first ten periods are significantly higher than those in the last ten periods (Wilcoxon rank sum test, $p = 0.016$).

In IC4, considering all periods, a regression over a constant shows that the difference between investments and the MSE is highly significant, whereas a Wilcoxon rank sum test indicates high significance only in the first five periods ($p = 0.01$).[23] However, the investments in the first ten periods are not significantly higher than those in the last ten periods (Wilcoxon rank sum test, $p = 0.146$). Again, there is no convergence to the MSE value of 1.27. In the last five periods, a Wilcoxon rank sum test shows significance at the 4%-level.

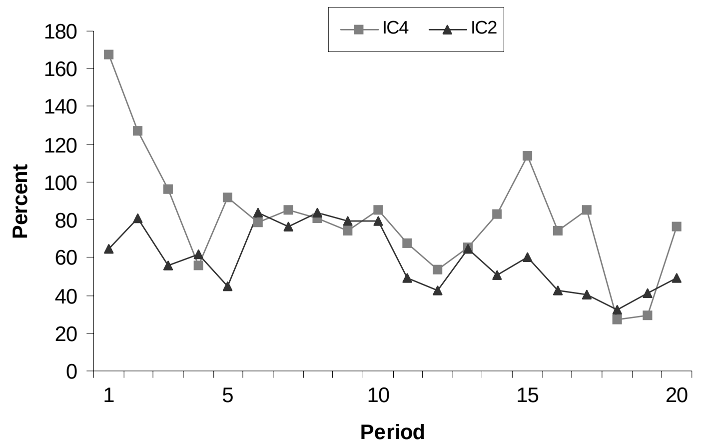

Figure 2.4: Deviation from the equilibrium under IC.

Inspection of Figure 2.4 shows that, in IC2 and IC4, the percentage deviations from the theoretical predictions are similar in most periods. Over all periods, the difference between the two treatments is not significant.

[22] This holds both for a Wilcoxon rank sum test and for a regression over a constant.

[23] The heterogeneity of investment choices under IC4 explains this discrepancy.

Having provided support for the comparative statics result (Hypothesis 2), we now investigate to which extent the asymmetric pure-strategy equilibria and the symmetric mixed-strategy equilibrium predict behavior within each IC treatment. In both treatments, the investments that are part of the asymmetric pure-strategy equilibria stand out. Even though, unsurprisingly, the players do not coordinate perfectly on such an equilibrium, the two equilibrium strategies are played particularly often.

Result 8 *For IC2, the frequency distribution exhibits a global maximum at 5. There is a local maximum at 0. For IC4, the frequency distribution exhibits a global maximum at 0. There is a local maximum at 5.*

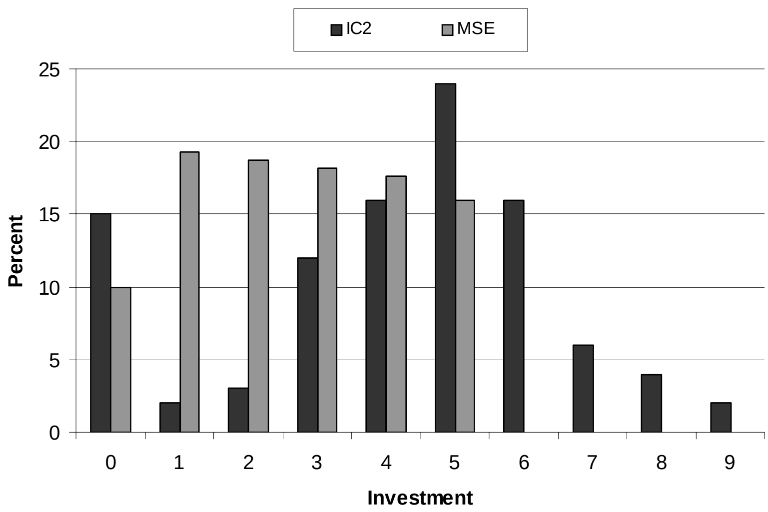

Figure 2.5: Investment distribution under IC2.

Figure 2.5 shows that, in IC2, the investment level of 5 is played in 24% and that of 0 in 15% of the cases. Figure 2.6 shows that, in IC4, the corresponding percentages are 17% and 43%. These qualitative properties show up clearly in almost every individual period.[24]

The next results concerns the relation to the MSE.

[24]For IC2, in 19 periods, the investment distribution exhibits a global maximum at 4 or 5. In 15 periods, there is a local maximum at 0. For IC4, in each period, the investment distribution exhibits a global maximum at 0 and a local maximum at 4 or 5.

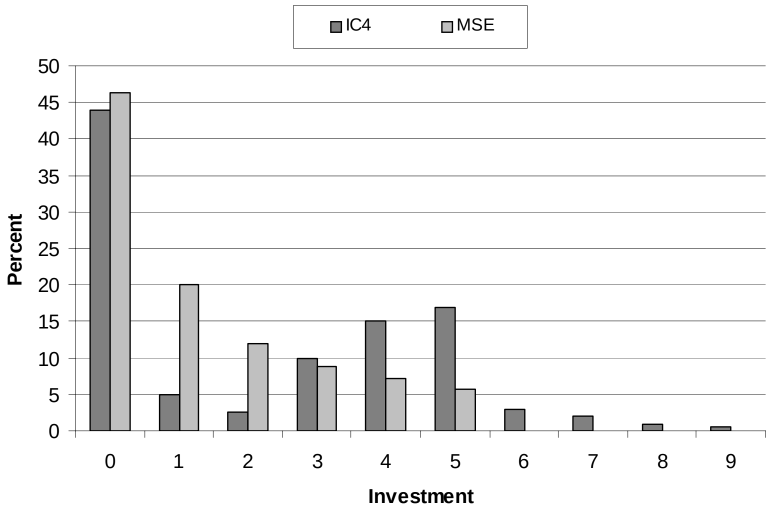

Figure 2.6: Investment distribution under IC4.

Result 9 *For IC2 and IC4, the MSE predicts the percentage of zero investments very well, but underpredicts the percentage of subjects who choose high investments.*

In both cases, low non-zero investments are chosen much less than predicted, and high investments more often. Figure 2.6 reveals that the MSE predicts the percentage of zero investments very well. However, also for IC4, overinvestment is substantial. The investment levels of 0, 1, and 2 are chosen less often than predicted; those from 3 to 9 more often than predicted.

Interval	$[0,1)$	$[1,2)$	$[2,3)$	$[3,4)$	$[4,5)$	$[5,6)$	$[6,7)$	$[7,8)$	$[8,9]$
IC2	1	1	6	6	11	6	2	1	0
IC4	8	9	7	4	7	1	0	0	0

Table 2.2: Subject distributions under IC.

Table 2.2 shows that the heterogeneity of investments reflects heterogeneity across players. For IC2, except that there is no local maximum in $[0,1)$, the distribution of the average investments is similar to the distribution of Figure 2.5. For IC4, except for the fact that the global maximum arises in $[1,2)$ instead of $[0,1)$, the distribution is similar to that of Figure 2.6.

To sum up, the number effects predicted by Hypothesis 2 are reflected quite well in the data. The point predictions of both types of equilibria are imperfect. Roughly speaking, the observed behavior corresponds to a mix between the symmetric mixed-strategy equilibrium and the asymmetric pure-strategy equilibrium.

Soft versus Intense Competition

We now turn to Hypothesis 3. We shall show that investments are higher in both IC treatments than in the corresponding SC treatments, even though the MSE predicts this only for SC2, in which case the equilibrium investments both for the discrete (2) and continuous benchmark (2.4) are lower than for the MSE under IC2 (2.62). The experiment provides evidence for this prediction.

Result 10 *As predicted, mean investments are higher for IC2 than for SC2.*

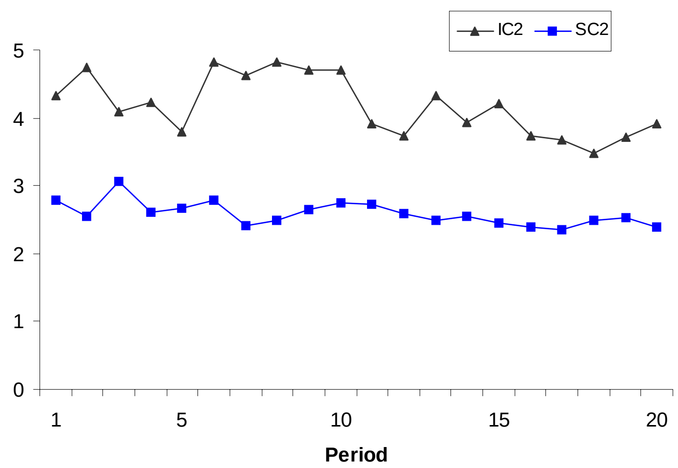

Figure 2.7: Mean investments for IC2 and SC2.

Over all periods, the difference between mean investments in IC2 and SC2 is highly significant. Figure 2.7 shows that the mean investment level under IC2 does not approach the one under SC2. Even in the last five periods, the difference remains highly significant.

While the comparative statics observation is consistent with equilibrium behavior, Figure 2.7 reveals that the higher investment in IC2 is reinforced by behavioral effects. In each period, overinvestment, measured as the percentage by which mean investments exceed the corresponding equilibrium value, is greater in IC2 than in SC2. The difference is highly significant when taking into account either all periods or the last five periods (see Figure 2.8).

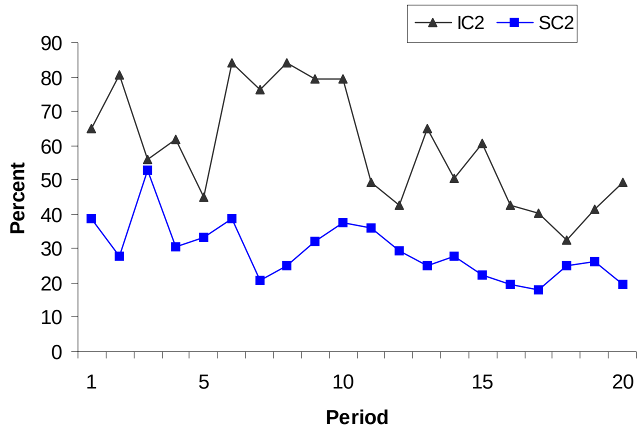

Figure 2.8: Deviation from the equilibrium for IC2 and SC2.

Interestingly, in the four-player case, the behavioral effects are so strong that they overturn the comparative statics prediction of Hypothesis 3, which was based on the observation that the equilibrium investments both for the continuous (1.69) and discrete benchmark (2) in SC4 are higher than for the MSE in IC4 (1.27).

Result 11 *Contrary to the prediction, mean investments are higher for IC4 than for SC4.*

Figure 2.9 shows that, except for period 18 and 19, the mean investment level is higher in IC4 than in SC4. Taking into account all periods, a regression over a constant shows that the difference between the two treatments is highly significant. However, a Wilcoxon rank sum test indicates significance at the 10%-level only in the first ten periods. Mean investments under IC4 seem to converge to those under SC4. However, a regression over a constant and a Wilcoxon rank sum test lead to different results. Considering the last five periods, the former shows no significant difference between the two treatments, whereas the latter exhibits significance at the 4%-level.[25]

[25] Again, due to the heterogeneity of the investment choices, which is generally more pronounced for IC than for SC, the statistical analysis is not unique.

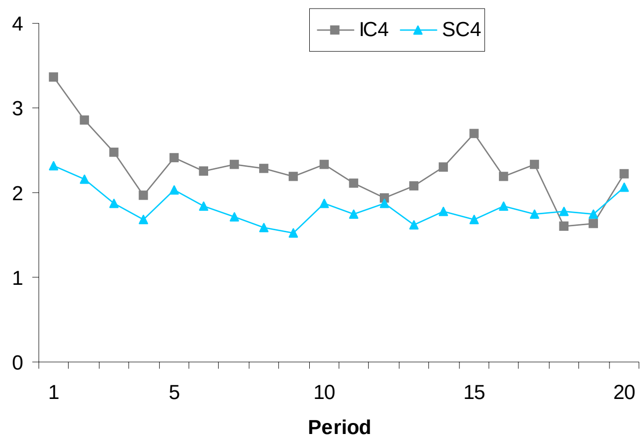

Figure 2.9: Mean investments for IC4 and SC4.

To sum up, investments are higher for IC than for SC, even in the four-player case where this does not correspond to the Nash prediction. Essentially, this results because the tendency to overinvest is more pronounced for IC than for SC.

The Efficiency of Investments

It is intuitively clear that the tendency to invest more than in the Nash equilibrium cannot be beneficial for firms. In this section, we measure the efficiency relative to joint profit maximization (JPM). Of course, this efficiency notion only considers the firms' interest. If consumers' interests were taken into account, the overinvestment would have to be interpreted as an efficiency-increasing deviation from the Nash equilibrium.

For IC, the maximal joint net payoff is achieved in each asymmetric pure-strategy equilibrium;[26] for SC, the joint profit maximization benchmark implies lower investments than the Nash equilibrium. Intuitively, investments impose a negative externality on the other players.[27] In all treatments, players overinvest

[26] As this equilibrium strategy has one player investing and considering that this player maximizes his own net payoff by choosing the investment level of 5, it follows that also the joint net payoff is maximal.

[27] For SC2, it can be shown that the maximal joint net payoff arises when the two players choose the investment level of 1; under SC4, when one player chooses 1 and the others 0.

relative to the JPM. To measure the extent of deviation from JPM, consider the efficiency rate (ER), defined as

$$ER = \frac{\textit{Mean Joint Net Payoff}}{\textit{Maximal Joint Net Payoff}}.$$

The ER considers the joint net payoff over all periods and groups in relation to the maximal joint net payoff. For IC, negative values emerge, which reflect the inefficiency resulting from overbidding. Under IC2, a value of -0.69 arises; under IC4, -0.87. The participants made losses over the 20 periods. In IC2, 22 of the 34 subjects earned a negative net payoff in at least 14 periods. In IC4, 13 of the 36 subjects earned a negative net payoff in at least 13 periods. No subject earned more than the initial endowment at the end of the IC sessions. On the other hand, the SC cases are relatively efficient. The SC2 treatment leads to an ER of 0.91. For SC4, the value is 0.77. Each participant earned more than the initial endowment.

2.4 Conclusion

This paper has analyzed the effects of more intense competition on investments in an experiment where a reduced form version of a simple two-stage R&D model has been implemented. In the first stage, firms whose marginal costs are identical ex-ante simultaneously invest in R&D. The investment leads to a decrease in marginal costs. In the second stage of the game, firms simultaneously choose quantities or prices in a homogenous good market.

When more intense competition is modeled as an increase of the number of firms for a given type of product market competition, the theoretical prediction is that, both for SC and IC, an increase in the number of agents yields lower mean investments. This hypothesis is confirmed in the lab. When more intense competition is modeled as a switch from Cournot to Bertrand competition, the observed investments increase, even though the MSE only predicts this in the two-player case.

An important limitation of our analysis concerns the very long run. As overinvestment tends to coincide with negative earnings in the IC game, it is not sustainable. Thus, in the very long run, firms must either adapt their behavior or they will disappear from the market. This feature is much less pronounced in the SC game, where overinvestment is compatible with positive earnings. One might therefore conjecture that, in the long run, whereas overinvestment remains in the SC case, it disappears in the IC case.

Acknowledgement For helpful comments and suggestions, we are grateful to Michael Kosfeld, Adrian Müller, and to participants at the following conferences: ESA (Rome), EEA (Budapest), EARIE (Valencia), and Swiss IO Day (Berne).

References

Bester, H., Petrakis, E.: "The Incentives for Cost Reduction in a Differentiated Industry." *International Journal of Industrial Organization* 11(4): 519-534 (1993).

Boone, J.: "Competition." *CEPR Discussion Paper*, No. 2636 (2000).

Delbono, F., Denicolò, V.: "R&D Investment in a Symmetric and Homogeneous Oligopoly: Bertrand versus Cournot." *International Journal of Industrial Organization* 8(2): 297-313 (1990).

Delbono, F., Denicolò, V.: "Incentives to Innovate in a Cournot Oligopoly." *Quarterly Journal of Economics* 106(3): 951-961 (1991).

Dufwenberg, M., Gneezy, U.: "Price Competition and Market Concentration: An Experimental Study." *International Journal of Industrial Organization* 18(1): 7-22 (2000).

Fischbacher, U.: "Z-Tree. Toolbox for Readymade Economic Experiments." *Experimental Economics* 10(2), 171-178 (2007).

Gilbert, R.J.: "Competition and Innovation." *Journal of Industrial Organization Education* 1(1), 1-23 (2006).

Halbheer, D., Fehr, E., Götte, L., Schmutzler, A.: "Self-Reinforcing Market Dominance." *SOI Working Paper*, No. 711, University of Zurich (2007).

Huck, S., Normann, H.T., Oechssler, J.: "Two are Few and Four are Many: Number Effects in Experimental Oligopolies." *Journal of Economic Behavior and Organization* 53(4): 435-446 (2004).

Isaac, R.M., Reynolds, S.S.: "Appropriability and Market Structure in a Stochastic Invention Model." *Quarterly Journal of Economics* 103(4): 647-671 (1988).

Isaac, R.M., Reynolds, S.S.: "Schumpeterian Competition in Experimental Markets." *Journal of Economic Behavior and Organization* 17: 59-100 (1992).

Lee, T., Wilde, L.L.: "Market Structure and Innovation: A Reformulation." *Quarterly Journal of Economics* 94(2): 429-436 (1980).

Orzen, H.: "Counterintuitive Number Effects in Experimental Oligopolies." Fothcoming in *Experimental Economics* (2008).

Sacco, D.: "Simplifying Experimental Design: One Stage vs. Two Stages." *Mimeo*, University of Zurich (2008).

Sacco, D., Schmutzler, A.: "All-Pay Auctions with Negative Prize Externalities: Theory and Experimental Evidence." *SOI Working Paper*, No. 806, University of Zurich (2008).

Schmutzler, A.: "The Relation between Competition and Innovation – Why is it such a Mess?" *SOI Working Paper*, No. 716, University of Zurich (2007).

Suetens, S.: "Cooperative and Noncooperative R&D in Experimental Duopoly Markets." *International Journal of Industrial Organization* 23: 63-82 (2005).

Vives, X.: "Innovation and Competitive Pressure." Forthcoming in *Journal of Industrial Economics* (2008).

Chapter 3

Competition and Investment: A U-shaped Relation

Dario Sacco

3.1 Introduction

A large game-theoretic literature deals with strategic investment decisions in an oligopolistic environment. One important class of papers focuses on the relation between the intensity of competition and process investment, typically using two-stage oligopoly games. This relation is generally regarded as ambiguous; depending on the precise definition of competitive intensity and the particular oligopolistic environment, competition may have positive or negative effects on investment (Gilbert, 2006; Schmutzler, 2007; Vives, 2008, forthcoming). In a general equilibrium setting, it has been argued that an inverse U-shaped relation is also conceivable (Aghion et al., 2005). This paper provides the surprising result that in a simple partial equilibrium framework a direct (non-inverted) U-relation between competition and investment can emerge, and it provides experimental support for the claim.

We consider a simple standard model: In the first stage of the game, duopolists choose cost-reducing investments; in the second stage, they engage in differentiated Cournot competition with linear inverse demand functions $p_i = a - q_i - bq_j$, where $b \in [0, 1]$. An increase in competition corresponds to a reduction in product differentiation (higher value of b). Thus, in the polar case where $b = 0$ there are essentially two monopolies; $b = 1$ corresponds to a homogeneous Cournot market. For symmetric firms, that is, identical initial marginal costs, an increase in competition reduces investments as long as product differentiation remains sufficiently strong; as products become sufficiently similar, however, a further increase in competition raises investments. This U-shape becomes even more pronounced for firms that are initially ahead of the competitors. However, if a firm lags substantially behind the competitor, increasing intensity of competition has an unambiguously negative effect on investments.

Thus, our model makes two main points. First, there is a U-shaped relation between intensity of competition and investment for a wide range of parameters; second, competition is more likely to have a negative effect on investments for strong laggards. As both points are made in a standard, but nevertheless rather specific model, it is important to understand the intuition. To this end, it is crucial to analyze the effects of the intensity of competition on marginal investment incentives, that is, the absolute value of the derivative of equilibrium profits (gross of investment costs) with respect to own marginal costs.[1] This marginal investment incentive itself depends in a non-monotone way on the competition parameter, reflecting the interaction of two countervailing effects. First, in the differentiated Cournot model, as in most reasonable cases, competition has a negative effect on the absolute mark-up that a firm can command in equilibrium. Hence, the positive effect on equilibrium demand that comes from a cost-reducing investment is less valuable. This points to a negative effect of competition on marginal investment incentives. However, as competition increases, the positive demand effect of increasing efficiency becomes more pronounced, suggesting a positive relation between competition and marginal investment incentives. The U-shape thus comes from the interaction of these two effects.

The difference between leaders and laggards can be explained similarly. Essentially, while both effects are still present for strong laggards, the positive effect becomes small for a firm that has a low demand because it is less efficient than the competitor.

[1] When investment incentives are increasing, investments in the subgame perfect Nash equilibrium of the game are also increasing under fairly weak additional conditions (see Schmutzler, 2007).

The paper also provides experimental evidence that supports the main results. In view of the simple structure of the model, we implement the experiment as a one-stage game where players choose investments, and then obtain the equilibrium profits corresponding to the resulting product market subgame.[2] We carried out a large number of experiments to identify the U-shaped relation between intensity of competition and investment and its robustness. We considered both symmetric and asymmetric settings. In both cases, we compared the investments for weak competition ($b = 1/10$) to intermediate competition ($b = 2/3$) and strong competition ($b = 1$). In the symmetric case, investments are lowest for intermediate competition, as predicted. However, there is overinvestment for all values of b. In the asymmetric case, the U-shaped relation arises for leaders, but the positive effect of moving from intermediate to strong competition is not as intense as predicted. For laggards, the predicted negative effect of competition on investment holds, but it is also less pronounced. Interestingly, to a large extent, these deviations reflect best responses to wrong beliefs that players have about the investments of the other subjects. That is, symmetric players and laggards believe that the competitor invests less than he actually does; rather, leaders believe than the competitor invests more than he actually does.

Though the focus is on the effects of competition on investment, our analysis also provides some insights into a related debate. A large literature has dealt with the issue of self-reinforcing market dominance. When firms differ in their initial efficiency levels, is there a tendency for these differences to become larger over time? The theoretical literature has identified forces that go in both directions (see Athey and Schmutzler, 2001). Though our model is only static, one of the key mechanisms for weak increasing dominance is present: Firms that are initially more efficient than others invest more. The asymmetric treatments of our experiments allow us to test whether increasing dominance actually arises. Indeed, this question is answered in the affirmative, essentially independent of the degree of competition. However, because leaders underinvest and laggards overinvest relative to the Nash equilibrium, the difference between the investments of leaders and laggards is obviously smaller than predicted by the model.

While the theoretical analysis of oligopolistic investment models is well established, the experimental analysis is still in its infancy. Except for two early

[2] For the case of symmetric duopolists engaging in differentiated Cournot competition, Sacco (2008) compares a two-stage experiment, where subjects take investment and quantity decisions, to the corresponding reduced-form game.

contributions of Isaac and Reynolds (1988, 1992) which deal with patent races and show that an increase in competition in the sense of a larger number of firms has a negative effect on investments, most of the literature has only developed recently. Sacco and Schmutzler (2008) consider homogenous Cournot and Bertrand settings with two and four firms.[3] Consistent with the earlier literature, they show that a larger number of firms lowers investments, whereas increasing competition in the sense of moving from Cournot to Bertrand has a positive effect on investments.

The first experimental paper that analyzes whether weak increasing dominance emerges is Halbheer et al. (2007). These authors also identify weak increasing dominance in a simple static Cournot model. They treat the homogenous case allowing for parameterizations reflecting spillovers between firms.

In this paper, we proceed as follows. Section 3.2 contains the theoretical framework. Section 3.3 discusses the experimental design and results. Section 3.4 concludes.

3.2 The Model

3.2.1 Differentiated Cournot-Duopoly

Consider firms $i = 1, 2$ producing heterogenous goods. Suppose without loss of generality that $c_1 \leq c_2$. If the inequality strictly holds, then firm 1 plays the leader's role; firm 2 is the laggard. Otherwise, firms are symmetric. The inverse demand functions are given by

$$p_i = a - q_i - bq_j, \ i \neq j, \tag{3.1}$$

where $b \in [0, 1]$, and $a > 0$.

For $b = 0$, equation (3.1) implies that both firms are monopolists. The other polar case $b = 1$ corresponds to a homogenous Cournot market. Thus, the higher b the higher the intensity of competition.

From profit maximization, the equilibrium quantity of firm i is given by

$$q_i = \frac{2Y_i - bY_j}{4 - b^2}, \tag{3.2}$$

[3] Suetens (2005) deals with a Cournot-Duopoly. However, she is not concerned with the effects of increasing competition.

where $Y_i \equiv a - c_i > 0$ represents the efficiency level.[4]

(3.2) implies the following equilibrium profits:

$$\Pi_i = \left(\frac{2Y_i - bY_j}{4 - b^2}\right)^2. \tag{3.3}$$

The cost reduction incentives are given by

$$\frac{\partial \Pi_i}{\partial c_i} = -\frac{8Y_i - 4bY_j}{(4 - b^2)^2} = -\frac{4q_i}{4 - b^2} < 0. \tag{3.4}$$

Given $q_i > 0$ and $b \in [0, 1]$, we have $\frac{\partial \Pi_i}{\partial c_i} < 0$, which means that a cost reduction increases firms' profits.

The effect of the intensity of competition on marginal incentives to invest is captured by

$$\frac{\partial^2 \Pi_i}{\partial c_i \partial b} = \frac{(16 + 12b^2) Y_j - 32bY_i}{(4 - b^2)^3}. \tag{3.5}$$

Investigation of (3.5) yields Proposition 11.

Proposition 11 *Suppose* $0 \leq b \leq 1$ *and* $0 < c_1 \leq c_2 < a$. *Then, the following holds: (i) For the leader, there is a U-shaped relation between the intensity of competition and marginal incentives to invest, with the minimum at* $0 < b \leq \frac{2}{3}$. *(ii) For the laggard, there is a U-shaped relation with the minimum at* $\frac{2}{3} \leq b \leq 1$ *if* $\frac{Y_1}{Y_2} \leq \frac{8}{7}$. *(iii) If* $\frac{Y_1}{Y_2} > \frac{8}{7}$, *the marginal incentives for the laggard are strictly decreasing. (iv) For symmetric firms, there is a U-shaped relation with the minimum at* $b = \frac{2}{3}$.

Proof. See Appendix. ■

It is straightforward to see from Proposition 11 that, for the laggard, the U-shaped relation is only given when c_1 and c_2 are sufficiently close.

3.2.2 The Investment Game

Consider now a two-stage game, where firms $i = 1, 2$ first engage in cost-reducing investments and then compete in the product market. The inverse demand functions are given by (3.1). Initial marginal costs are denoted as c_i^0 and corresponding efficiency levels as $Y_i^0 \equiv a - c_i^0 > 0$. In the following, we assume $c_1^0 \leq c_2^0$; thus, $Y_1^0 \geq Y_2^0$. In the first stage, firms simultaneously choose investments $y_i \in [0, c_i^0)$,

[4] For the leader and symmetric firms, (3.2) is always positive; for the laggard, if $b < \frac{2Y_2}{Y_1}$.

resulting in marginal costs $c_i = c_i^0 - y_i$. The efficiency level of firm i after the investment stage is given by $Y_i = Y_i^0 + y_i$. The investment costs are quadratic and given by ky_i^2, where $k > 0$. In the second stage, firms simultaneously choose quantities, that is, they compete à la Cournot.

According to (3.3), the net profit of firm $i = 1, 2$ in the first stage of the game is given by

$$\pi_i = \left(\frac{2(Y_i^0 + y_i) - b(Y_j^0 + y_j)}{4 - b^2} \right)^2 - ky_i^2, \; i \neq j. \tag{3.6}$$

The maximization of (3.6) with respect to y_i leads to

$$\frac{\partial \pi_i}{\partial y_i} = \frac{8\left(Y_i^0 + y_i\right) - 4b\left(Y_j^0 + y_j\right)}{\left(4 - b^2\right)^2} - 2ky_i \equiv 0. \tag{3.7}$$

The second-order condition is given by

$$\frac{\partial^2 \pi_i}{\partial y_i^2} = \frac{8}{\left(4 - b^2\right)^2} - 2k < 0. \tag{3.8}$$

Note that (3.8) is fulfilled $\forall b \in [0, 1]$ if $k > \frac{4}{9}$.

From (3.7), it follows that

$$y_i = \frac{4Y_i^0 - 2b\left(Y_j^0 + y_j\right)}{k\left(4 - b^2\right)^2 - 4}. \tag{3.9}$$

Relation (3.9) implies the following equilibrium investments:

$$y_i^* = \frac{(4 + 4b^2k - 16k)Y_i^0 + (8bk - 2b^3k)Y_j^0}{8k(4 - b^2) - k^2\left(4 - b^2\right)^3 - 4}. \tag{3.10}$$

Note that (3.10) is positive if Y_i^0 and Y_j^0 are sufficiently close.[5]

The difference between leader's and laggard's equilibrium investments is given by

$$y_1^* - y_2^* = \frac{2(c_1^0 - c_2^0)}{k(b - 2)(4 - b^2) + 2}. \tag{3.11}$$

Note that (3.11) is positive $\forall c_1^0 < c_2^0$, $\forall b \in [0, 1]$, and $\forall k > 0$.[6] That is, the firm that is initially more efficient invests more than the other firm, implying that increasing dominance arises.

[5] For instance, consider $b = 1$ and $k = 1$. Then, (3.10) is positive if $\frac{Y_i^0}{Y_j^0} > \frac{3}{4}$.

[6] For $c_1^0 = c_2^0$, (3.11) is obviously zero.

3.2.3 Choosing the Parameters

In this section, we consider a specific parameterization that we also use in the experiment. We first treat the asymmetric case. Let $a = 50$, $k = 1$, $c_1^0 = 21$, $c_2^0 = 25$. For these parameters,

$$\frac{Y_1^0}{Y_2^0} = \frac{a - c_1^0}{a - c_2^0} = \frac{29}{25} > \frac{8}{7}. \tag{3.12}$$

For the leader, there is a U-shaped relation between intensity of competition and incentives to invest by Proposition 11. For the laggard, (3.12) implies strictly decreasing investments.[7] Figure 3.1 shows the plots of the leader's and laggard's equilibrium investments for $b \in [0, 1]$.

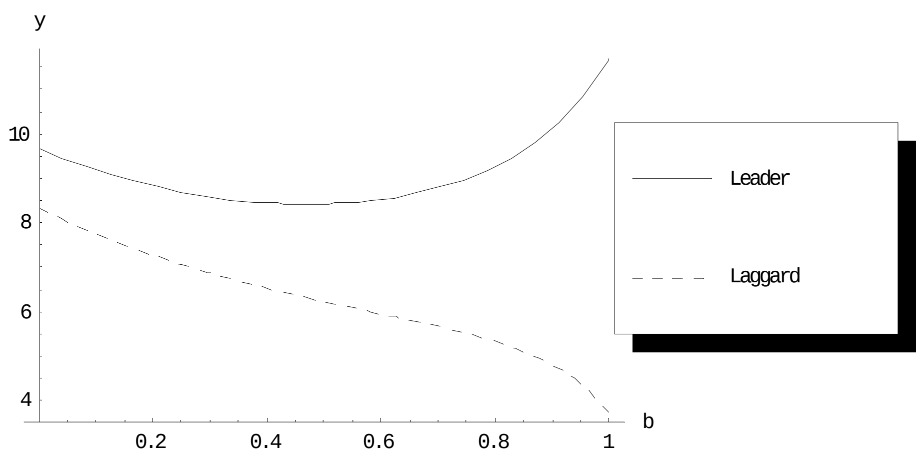

Figure 3.1: Leader's and laggard's investments.

In the experiment, we consider three cases for b, which correspond to different intensities of competition: $b = 1/10$ (weak), $b = 2/3$ (intermediate), and $b = 1$ (strong). For the leader, the equilibrium investments are as follows:

$$\begin{cases} b = 1/10 \Rightarrow y_1^* = 9.18 \\ b = 2/3 \Rightarrow y_1^* = 8.68 \\ b = 1 \Rightarrow y_1^* = 11.70 \end{cases}. \tag{3.13}$$

[7] Actually, to ensure that laggard's investments are strictly decreasing, ex-ante marginal costs may be less close than stated in Proposition 11. This can be shown through the derivative of (3.10) for $i = 2$ with respect to b; (3.12) becomes $\frac{Y_1^0}{Y_2^0} \geq \frac{124}{121}$.

For the laggard, we have:

$$\begin{cases} b = 1/10 \Rightarrow y_2^* = 7.75 \\ b = 2/3 \Rightarrow y_2^* = 5.75 \\ b = 1 \Rightarrow y_2^* = 3.70 \end{cases} . \tag{3.14}$$

Consider now the symmetric case. Figure 3.2 shows the plot of the equilibrium investments for $a = 50,\ k = 1,\ c_1^0 = c_2^0 = 21$, and $b \in [0, 1]$.

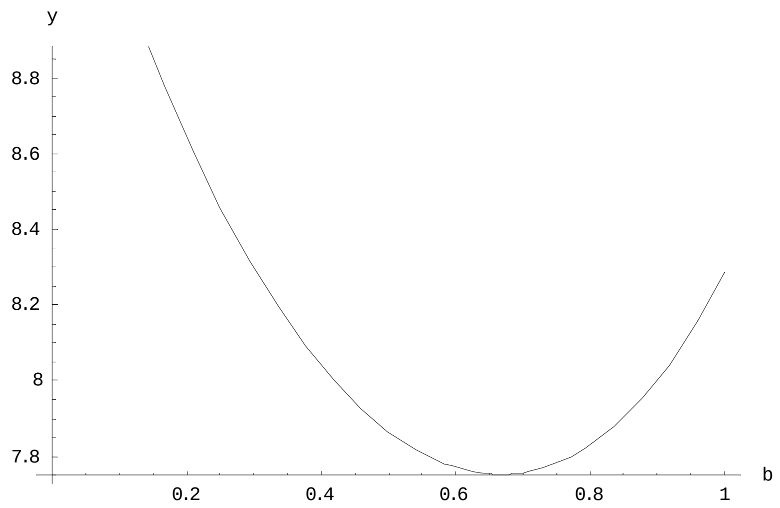

Figure 3.2: Investments of the symmetric firms.

For the three values of the competition parameter b, the following equilibrium investments $y_1^* = y_2^* = y^*$ arise:

$$\begin{cases} b = 1/10 \Rightarrow y^* = 9.09 \\ b = 2/3 \Rightarrow y^* = 7.75 \\ b = 1 \Rightarrow y^* = 8.28 \end{cases} . \tag{3.15}$$

For both firms, there is a U-shaped relation between intensity of competition and investments.[8]

[8] By Proposition 11, the minimum of the investment function lies at $b = 2/3$.

3.3 The Experiment

3.3.1 Experimental Design and Procedures

The game implemented in the experiment is a reduced form version of the described two-stage game. To focus on investment choices which we restricted to $y_i \in \{0, 1, ..., 14\}$, we reduced the game to the first stage, that is, to the investment stage. We did not model the product market stage explicitly. Instead, for each investment profile, players earned the unique Nash equilibrium profits of the corresponding subgame. This was a deliberate modeling choice ensuring that, whatever deviations from the equilibrium investments might arise, they do not result from anticipations of second-period deviations from the product market equilibrium.

In October and November 2007, we conducted eight experimental sessions at the University of Zurich. The participants were undergraduate students from various disciplines. In the first four sessions, we implemented the symmetric case; in the last four, the asymmetric case with the leader-laggard structure. Each session had 20 periods. In each session, there was a switch of the competition parameter after period 10. That is, participants played the game for one parameterization in the first ten periods and for the other parameterization in the second ten periods. In different sessions, we reversed the order of the parameterizations to allow for sequencing effects. Table 3.1 gives an overview of the sessions.

Symmetric/Asymmetric	Period 1-10	Period 11-20
S1/A1	$b = 0.1$	$b = 0.67$
S2/A2	$b = 0.67$	$b = 0.1$
S3/A3	$b = 0.67$	$b = 1$
S4/A4	$b = 1$	$b = 0.67$

Table 3.1: Four symmetric and four asymmetric sessions.

In seven of eight sessions, there were 36 subjects.[9] This led to a total of 5640 investment observations. Moreover, in each period, subjects were asked to give a belief about the investment of the other group member.

In the asymmetric sessions, the roles of leader and laggard were randomly

[9] In S3, there were 30 participants.

assigned and there was no switch over the 20 periods. No subject participated in more than one session. We built fixed matching groups of 6 people for statistical reasons. The participants were randomly matched into groups of size two within the matching groups. At the end of each period, subjects were informed about the investment level of the other group member and their own net profit for that period. In each session, participants received an initial endowment of CHF 20 (≈EUR 12). Average earnings including the endowment were CHF 38 (≈EUR 24) for S1 and S2, and CHF 30 (≈EUR 19) for S3 and S4. In A1 and A2, average earnings were CHF 40 (≈EUR 25) and CHF 32 (≈EUR 20) for leaders and laggards, respectively. In A3 and A4, leaders earned on average CHF 35 (≈EUR 22); laggards CHF 24 (≈EUR 15). Sessions lasted about 2 hours each. The experiment was programmed and conducted with the software z-Tree (Fischbacher, 2007).

3.3.2 Results

In this section, we discuss the experimental results. To analyze the effects of varying the intensity of competition on the investment behavior, we consider three different parameterizations $(b = 1/10, b = 2/3, b = 1)$. First, we treat the asymmetric setting; second, the symmetric case.

The Asymmetric Setting

In the following, we analyze the first ten and the last ten periods of the four asymmetric sessions in turn. After that, to focus on sequencing effects, we compare A1 to A2, and A3 to A4; that is, we consider pairs of sessions which include the same values of b, but differ with respect to the order of the parameterizations.

Investments in the two period ranges The theoretical prediction is that leaders invest more than laggards. Further, for leaders, there is a U-shaped relation between intensity of competition and investment; for laggards, there is a negative relation. The experiment provides evidence for these predictions both for the first ten and for the last ten periods. However, the strength of the U-shaped relation is different for the two period ranges. We start with the first period range.

Result 12 *In the first ten periods, leaders invest more than laggards. Leaders' investments are lowest for intermediate competition. Laggards' investments strictly decrease with increasing intensity of competition.*

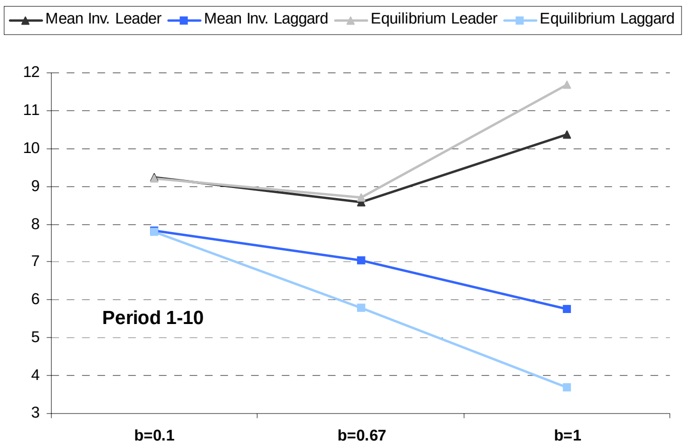

Figure 3.3: Leaders' and laggards' investment in period 1-10.

Figure 3.3 reveals that increasing dominance arises. For all values of b, a regression over a constant and a Wilcoxon rank sum test show high significance $(p < 0.01)$ when considering the difference between leaders' and laggards' investments. Further, for leaders, there is underinvestment when competition is strong $(b = 1)$; for laggards, there is overinvestment when competition is intermediate and strong $(b = 0.67, b = 1)$. A regression over a constant shows that, for leaders, there is no significant difference between investments and Nash equilibrium for $b = 0.1$ and $b = 0.67$. However, this result is not fully supported by a Wilcoxon rank sum test which yields significance at the 10%-level. On the other hand, the difference between actual and equilibrium investments is highly significant when competition is strong. For laggards, there is no significant deviation from the equilibrium for $b = 0.1$; high significance is given for $b = 0.67$ and $b = 1$. These deviations from the equilibrium can be explained through players' beliefs.[10]

Leaders believe that laggards invest more than they actually do. This is shown in Figure 3.4. Interestingly, given the wrong beliefs, leaders essentially choose the optimal investment level. In fact, the best response to the own beliefs

[10] Observe that own investments and beliefs about other players' investments are strategic substitutes.

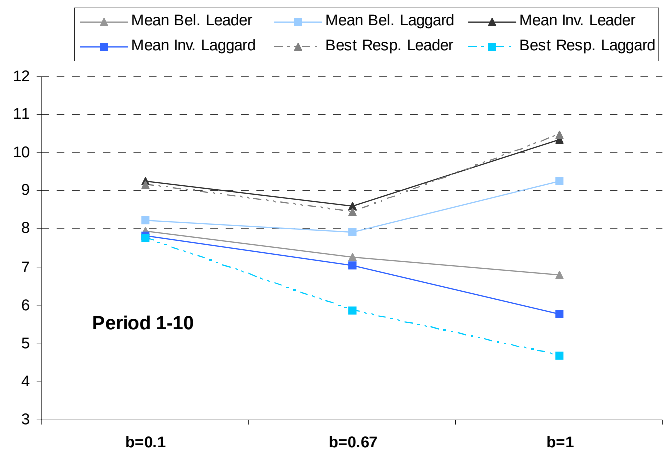

Figure 3.4: Leaders' and laggards' belief in period 1-10.

almost coincides with actual investments; a regression over a constant and a Wilcoxon rank sum test yield no significant difference. Rather, laggards believe that leaders invest less than they actually do. This explains the overinvestment of the laggards. However, their investments are even higher than the best response to the wrong beliefs. The asymmetry between leaders and laggards – the former best-respond to their beliefs while the laggards do not – is astonishing. One explanation may be that laggards deliberately hurt leaders who have an exogenous advantage.

We consider now the last ten periods. The investment behavior is similar to that discussed above.

Result 13 *In the last ten periods, leaders invest more than laggards. Leaders' investments are lowest for intermediate competition. Laggards' investments strictly decrease with increasing intensity of competition.*

Figure 3.5 shows that, like in the first ten periods, increasing dominance emerges. The difference between leaders' and laggards' investments is highly significant for each parameterization.[11] Moreover, for leaders, there is slight overinvestment when competition is weak and intermediate, and striking underinvestment for strong competition. For laggards, there is overinvestment for all values of b. Regarding the deviation from the equilibrium, a regression over a

[11] This is supported both by a regression over a constant and a Wilcoxon rank sum test.

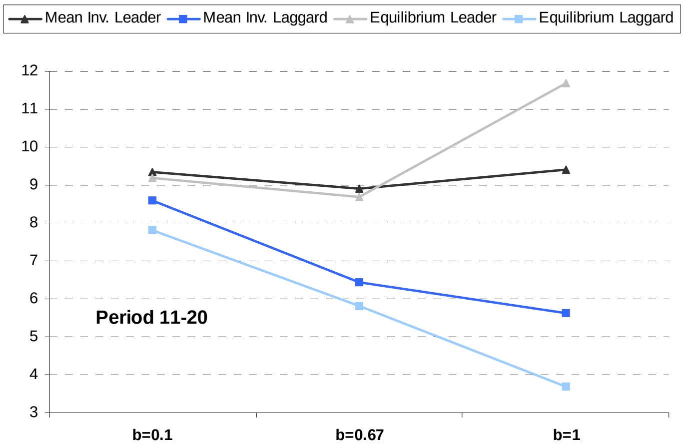

Figure 3.5: Leaders' and laggards' investment in period 11-20.

constant and a Wilcoxon rank sum test yield high significance for each parameter value and player's role. Again, subjects' beliefs are helpful to understand the investment behavior.

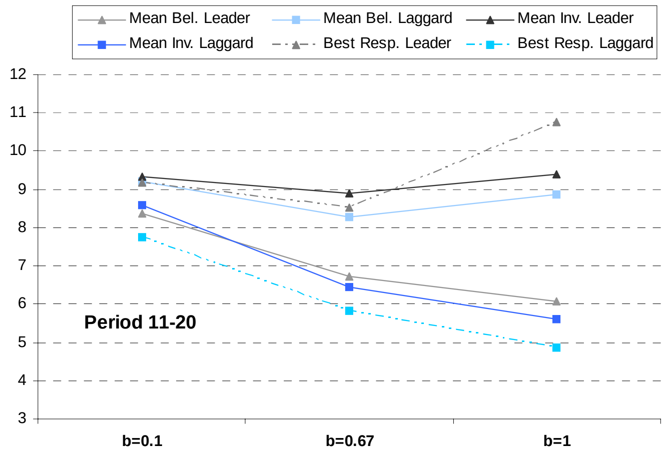

Figure 3.6: Leaders' and laggards' belief in period 11-20.

Figure 3.6 reveals that, for leaders, the underinvestment for $b = 1$ is related to wrong beliefs about laggards' investments. However, in contrast to the first ten periods, wrong beliefs do not fully explain the underinvestment behavior. In fact, investments of leaders are even lower than the best response to the own overestimated beliefs. Further, for laggards, the overinvestment results from underestimating leaders' investments. Like in the first ten periods, laggards invest even more than the best response to the wrong beliefs.

Results 12 and 13 have shown that, for leaders, a U-shaped relation emerges; for laggards, there is a negative relation. To test how strong these relations are, we consider the following random-effects model:

$$Y^i_{t,k} = \beta_0 + \beta_1\delta^i_{weak,k} + \beta_2\delta^i_{strong,k} + e^i_{t,k} + \mu^i_k, \tag{3.16}$$

where $e^i_{t,k}$ is a residual term which is independent across groups k; μ^i_k, which captures the random effects, is uncorrelated with each explanatory variable in all time periods. The dummy variable $\delta^i_{weak,k}$ takes the value 1 if the investment of subject i belonging to group k occurs in the first ten periods of A1 or in the last ten periods of A2, where the intensity of competition is weak. Otherwise, it takes the value 0. Similarly, $\delta^i_{strong,k}$ takes the value 1 if $b = 1$.

Estimates are shown in Table 3.2.

Table 3.2: Effects of the intensity of competition on the investment behavior.

Variable	Period 1-10 *Leader*	Period 11-20 *Leader*	Period 1-10 *Laggard*	Period 11-20 *Laggard*
const	8.5944***	8.8972***	7.0333***	6.4416***
	(0.2593)	(0.2694)	(0.2790)	(0.2539)
weak	0.6611**	0.4361*	0.7944**	2.1416***
	(0.4041)	(0.4659)	(0.3969)	(0.4657)
strong	1.7666***	0.5027*	−1.2722***	−0.8194**
	(0.4367)	(0.4898)	(0.5254)	(0.4927)

Note: Random-effects GLS regression. * denotes significance at the 10%-level, ** at the 5%-level, *** at the 1%-level. Robust standard errors in parentheses.

The reference variable is intermediate competition. First, consider leaders. For period 1 to 10, the coefficients related to *weak* and *strong* are positive and significant at the 5% and 1%-level, respectively. Investments for $b = 0.1$ are 0.6611 units higher than for $b = 0.67$; those for $b = 1$ are 1.7666 units higher than for $b = 0.67$. This implies that the U-shaped relation is quite strong even though there is underinvestment for $b = 1$. Rather, in period 11 to 20, we denote a clearly weaker relationship. The coefficients for *weak* and *strong* are positive and significant at the 10%-level. Thus, for $b = 1$, underinvestment is more pronounced in the last ten periods. Second, consider laggards. The negative relation is substantial in each period range. The coefficients for *weak* are positive and significant at the 5% and 1%-level, respectively; those for *strong* are negative and significant at the 1% and 5%-level, respectively.

We can now summarize the findings related to Table 3.2 in the following result.

Result 14 *For leaders, the U-shaped relation is stronger in the first ten than in the last ten periods. For laggards, the negative relation is strong no matter what period range is considered.*

Sequencing effects So far we have discussed the investment behavior in the two period ranges. In the following, we analyze whether sessions involving the same values of b but a different order of the parameterizations lead to similar results. To this end, we compare the investment distributions in A1 to those in A2. Analogously, for A3 and A4. Dealing with the investment distributions also allows us to highlight the heterogeneity of player behavior. We start with A1 and A2, where $b = 0.1$ and $b = 0.67$ are the relevant parameters.

Result 15 *For A1 and A2, more intense competition shifts the leaders' and laggards' investment distribution to the left.*

According to prediction, leaders and laggards choose in both sessions higher investments when competition is less intense. This holds no matter what competition parameter is implemented first. For leaders, the investment distributions in A1 are shown in Figure 3.7.

Switching from weak to intermediate competition shifts the global maximum from 9 (34%) to 8 (56%). For laggards, the investment distributions in A1 are shown in Figure 3.8. More intense competition shifts the global maximum from 8 (47%) to 6 (54%).

The analysis of A2, where the parameterization order is reversed, leads to very similar results. We therefore omit additional considerations related to A2.

In the following, we investigate sessions A3 and A4, where the parameters involved are $b = 0.67$ and $b = 1$.

Result 16 *For A3 and A4, more intense competition shifts the laggards' investment distribution to the left; the shift of the leaders' distribution to the right is more pronounced in A4 than in A3.*

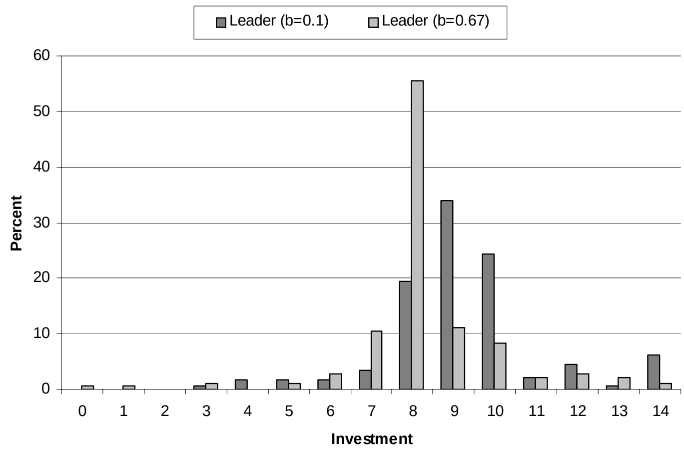

Figure 3.7: Leaders' investment distributions in A1.

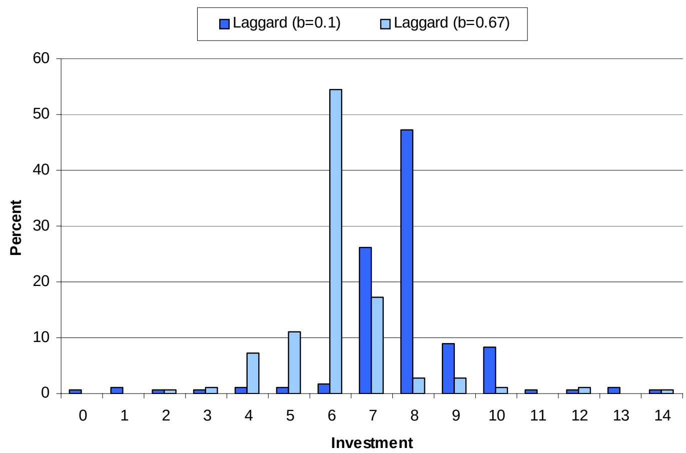

Figure 3.8: Laggards' investment distributions in A1.

As predicted, in both sessions, laggards choose lower investments when competition is more intense. For leaders, there is a difference between A3 and A4. Consistent with Result 14, the distribution in A3 does not clearly shift to the right with increasing competition. The parameter switch in A4 has a greater impact on investments of leaders. Figure 3.9 shows the leaders' investment distributions in A4.

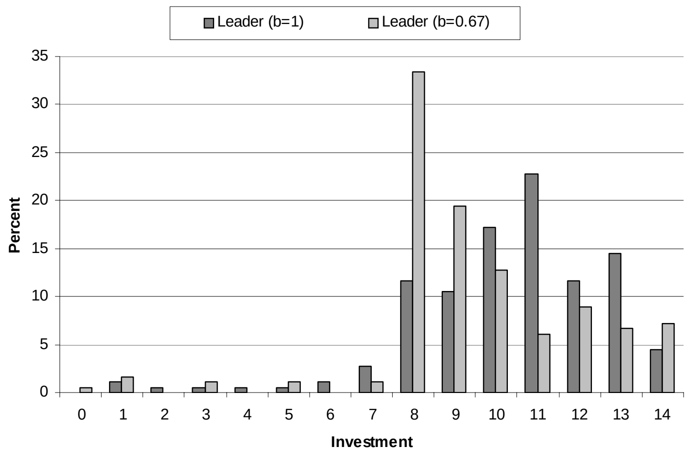

Figure 3.9: Leaders' investment distributions in A4.

The switch from strong to intermediate competition shifts the global maximum from 11 (23%) to 8 (33%). Figure 3.10 shows the investment distributions of laggards in A4. Less intense competition shifts the global maximum from 4 (19%) to 6 (27%).

The Symmetric Setting

In the following, we consider the symmetric case. Like in the asymmetric setting, we first analyze the investment behavior in the two period ranges, then the sequencing effects.

Investments in the two period ranges The theoretical prediction is that, for both players, there is a U-shaped relation between intensity of competition and investment. The experiment provides evidence for this prediction both for the first ten and last ten periods. Again, like in the asymmetric setting, the strength of the U-shaped relation is different for the two period ranges.

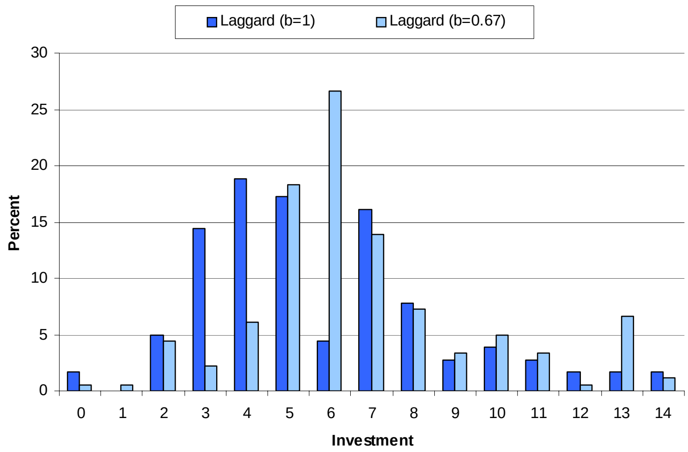

Figure 3.10: Laggards' investment distributions in A4.

Result 17 *In the first ten periods, investments are lowest for intermediate competition.*

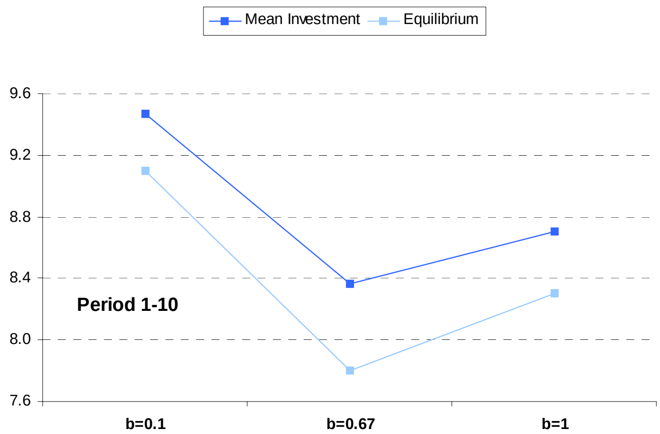

Figure 3.11: Mean investment in period 1-10.

Figure 3.11 reveals that there is overinvestment for all values of b. Both a regression over a constant and a Wilcoxon rank sum test show that the difference between observed and equilibrium investments is highly significant. The overinvestment behavior reflects underestimated beliefs.

Figure 3.12 shows that subjects believe that their group members invest less

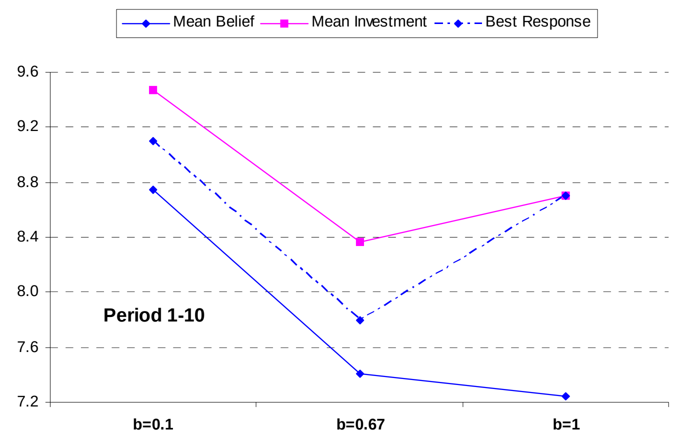

Figure 3.12: Mean belief in period 1-10.

than they actually do. However, for $b = 0.1$ and $b = 0.67$, mean investments are even higher than the best response to the wrong beliefs. For $b = 1$, mean investments exactly coincide with the best response to the underestimated beliefs.

Next, we consider the last ten periods, for which the investment behavior is similar to the other period range.

Result 18 *In the last ten periods, investments are lowest for intermediate competition.*

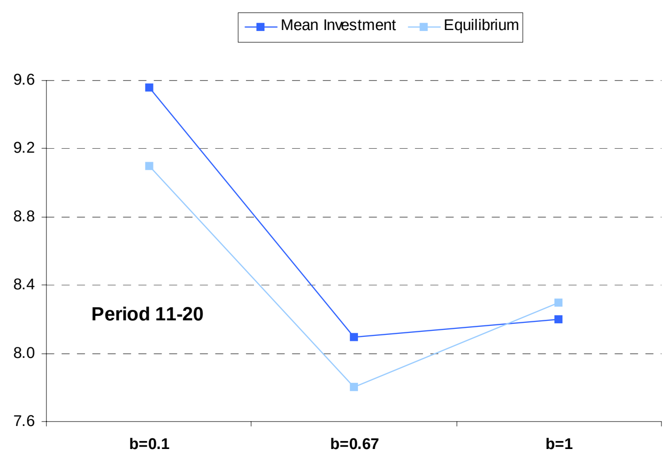

Figure 3.13: Mean investment in period 11-20.

For weak and intermediate competition, Figure 3.13 indicates overinvestment; for strong competition, there is slight underinvestment. For $b = 0.1$ and $b = 0.67$, both a regression over a constant and a Wilcoxon rank sum test show that the difference between observed and equilibrium investments is highly significant. For $b = 1$, there is no significant difference.

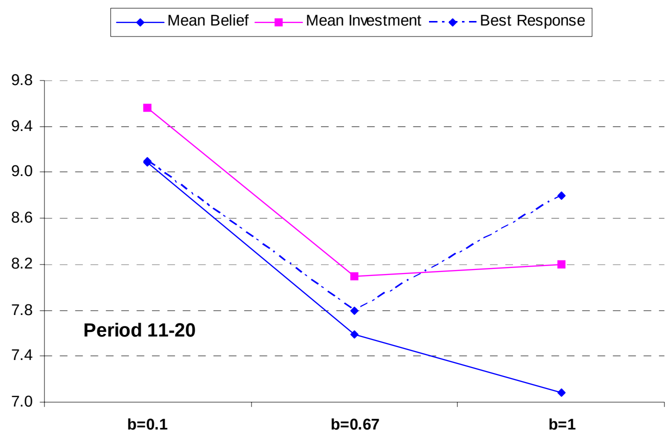

Figure 3.14: Mean belief in period 11-20.

For weak and intermediate competition, Figure 3.14 reveals that the overinvestment can be partly explained through the underestimated beliefs. However, mean investments are even higher than the best response to the wrong beliefs. For strong competition, the underestimated beliefs do not lead to overinvestment which would arise by best-responding.

To test the strength of the U-shaped relations shown in Result 17 and 18, consider the random-effects model given by (3.16). Estimates are shown in Table 3.3. For period 1 to 10, the coefficient related to *weak* is positive and significant at the 1%-level. The coefficient for *strong* is positive and significant at the 10%-level. This means that the decrease in investment is substantial when switching from weak to intermediate competition; the increase when switching from intermediate to strong competition is less pronounced. For period 11 to 20, the coefficient for *weak* is positive and significant at the 1%-level; the one for *strong* is positive but not significant. This implies that the decrease in investment is strong, the increase extremely weak.

Table 3.3: Effects of the intensity of competition on the investment behavior.

Variable	Period 1-10	Period 11-20
const	8.3590***	8.0916***
	(0.1684)	(0.1644)
weak	1.1075***	1.4666***
	(0.2384)	(0.2239)
strong	0.3436*	0.1050
	(0.2715)	(0.3502)

Note: Random-effects GLS regression. * denotes significance at the 10%-level, *** at the 1%-level. Robust standard errors in parentheses.

Summarizing we get Result 19.

Result 19 *The U-shaped relation is stronger in the first ten than in the last ten periods.*

Sequencing effects In the following, we compare S1 to S2, and S3 to S4. We start with S1 and S2, where $b = 0.1$ and $b = 0.67$ are the relevant parameters.

Result 20 *For S1 and S2, more intense competition shifts the players' investment distribution to the left.*

According to prediction, subjects choose in both sessions higher investments when competition is less intense. For the considered two sessions, the distributions look similar. Figure 3.15 concerns S1.

For weak competition, the global maximum is at 9 and chosen in 51% of the cases. In fact, playing 9 represents a weakly dominant strategy.[12] Switching to intermediate competition shifts the global maximum to 8 (32%). The last considerations refer to S3 and S4, where $b = 0.67$ and $b = 1$ are the parameters involved.

Result 21 *For S3 and S4, more intense competition does not unambiguously shift the players' investment distribution to the right.*

[12] In S1, we have eleven subjects choosing the investment level of 9 in each of the ten periods, sixteen subjects in at least eight periods. There are 28 subjects which invest on average between 8 and 10.

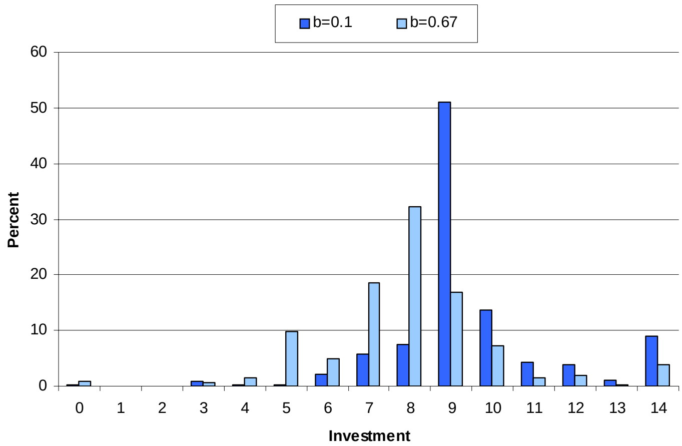

Figure 3.15: Investment distributions in S1.

In contrast to prediction, higher intensity of competition does not clearly lead to higher investments. This is consistent with Result 19. Figure 3.16, which refers to S3, shows that the distributions are similar.

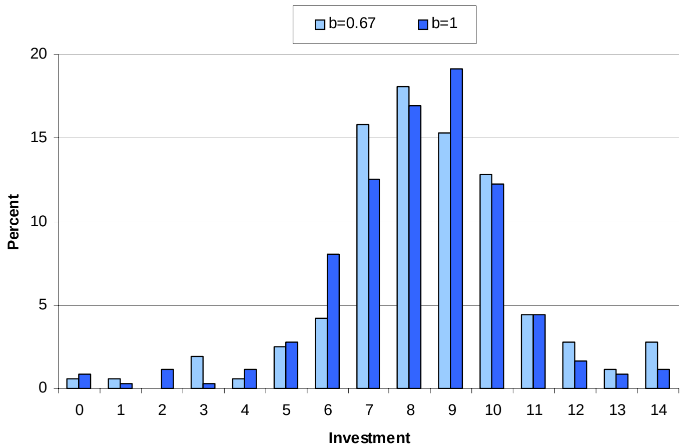

Figure 3.16: Investment distributions in S3.

3.4 Conclusion

We have analyzed the effects of varying the intensity of competition on investment incentives in an experiment, where we implemented a reduced form version of a two-stage game. In the first stage, duopolists choose cost-reducing investments. In the second stage, they choose quantities in a heterogenous good market. Increasing competition corresponds to decreasing product differentiation.

We considered two settings: A symmetric and an asymmetric one. In the symmetric setting, firms' initial marginal costs are identical. In the asymmetric setting, there is a leader-laggard structure. The leader has lower marginal costs ex-ante. We have shown that, for symmetric firms and leaders, there is a U-shaped relation between the intensity of competition and investment. If the ex-ante cost difference between leader and laggard is sufficiently high, there is a negative relation for the laggard. Otherwise, the laggard also exhibits a U-shaped relation. Moreover, the leader invests more than the laggard; that is, increasing dominance arises.

The experimental sessions mostly support the theoretical predictions. For symmetric players and leaders, the U-shaped relation emerges; for laggards, as predicted, there is a negative relation. Moreover, leaders invest more than laggards, providing evidence for increasing dominance. However, in both settings, there are deviations from the equilibrium. To a large extent, these deviations reflect best responses to wrong beliefs. In the symmetric setting, there is overinvestment no matter which intensity of competition is implemented. In the asymmetric setting, leaders underinvest under strong competition and laggards mostly overinvest.

Acknowledgement For helpful comments and suggestions, I am grateful to Armin Schmutzler, Donja Darai, and to participants at the following conferences: IMEBE (Alicante), ESA (Pasadena), and EEA (Milan).

Appendix

Proof of Proposition 11

(3.5) leads to the following results.

If $\frac{2}{3} < b \leq 1$ and $0 < c_1 \leq c_2 < a$, then $\frac{\partial^2 \Pi_1}{\partial c_1 \partial b} < 0$. Further, (3.5) has a unique zero $\hat{b} \in (0, \frac{2}{3}]$. $\hat{b}$ is given by

$$\hat{b} = \frac{4 - 2\sqrt{-3Q^2 + 4}}{3Q}, \tag{3.17}$$

where $Q = \frac{Y_2}{Y_1} \leq 1$. Thus, $Q^2 < \frac{4}{3}$ ensures the existence of $\hat{b}$. If $\frac{Y_2}{Y_1} \to 1$, then $\hat{b} \to \frac{2}{3}$.

If $0 \leq b < \frac{2}{3}$ and $0 < c_1 \leq c_2 < a$, then $\frac{\partial^2 \Pi_2}{\partial c_2 \partial b} > 0$. Further, $\frac{\partial^2 \Pi_2}{\partial c_2 \partial b}$ has a unique zero $\tilde{b} \in \left[\frac{2}{3}, 1\right]$. $\tilde{b}$ is given by (3.17), where $Q = \frac{Y_1}{Y_2}$. We need $Q^2 \leq \frac{4}{3}$ to ensure the existence of $\tilde{b}$, and $Q^2 \leq \frac{64}{49}$ to ensure that $\tilde{b} \in [0, 1]$. If $\frac{64}{49} < Q^2 \leq \frac{4}{3}$, then $\tilde{b} \in (1, \frac{2}{\sqrt{3}}]$. If $Q^2 > \frac{4}{3}$, there is no $\tilde{b}$.

This yields statements (i) to (iv).

References

Aghion, P., Bloom, N., Blundell, R., Griffith, R., Howitt, P.: "Competition and Innovation: An Inverted-U Relationship." *The Quarterly Journal of Economics* 120(2): 701-728 (2005).

Athey, S., Schmutzler, A.: "Investment and Market Dominance." *RAND Journal of Economics* 32(1): 1-26 (2001).

Fischbacher, U.: "Z-Tree. Toolbox for Readymade Economic Experiments." *Experimental Economics* 10(2), 171-178 (2007).

Gilbert, R.J.: "Competition and Innovation." *Journal of Industrial Organization Education* 1(1), 1-23 (2006).

Halbheer, D., Fehr, E., Götte, L., Schmutzler, A.: "Self-Reinforcing Market Dominance." *SOI Working Paper*, No. 711, University of Zurich (2007).

Isaac, R.M., Reynolds, S.S.: "Appropriability and Market Structure in a Stochastic Invention Model." *Quarterly Journal of Economics* 103(4): 647-671 (1988).

Isaac, R.M., Reynolds, S.S.: "Schumpeterian Competition in Experimental Markets." *Journal of Economic Behavior and Organization* 17: 59-100 (1992).

Sacco, D.: "Simplifying Experimental Design: One Stage vs. Two Stages." *Mimeo*, University of Zurich (2008).

Sacco, D., Schmutzler, A.: "Competition and Innovation: An Experimental Investigation." *SOI Working Paper*, No. 807, University of Zurich (2008).

Schmutzler, A.: "The Relation between Competition and Innovation – Why is it such a Mess?" *SOI Working Paper*, No. 716, University of Zurich (2007).

Suetens, S.: "Cooperative and Noncooperative R&D in Experimental Duopoly Markets." *International Journal of Industrial Organization* 23: 63-82 (2005).

Vives, X.: "Innovation and Competitive Pressure." Forthcoming in *Journal of Industrial Economics* (2008).

Chapter 4

Simplifying Experimental Design: One Stage vs. Two Stages

Dario Sacco

4.1 Introduction

Many experiments dealing with two-stage models are implemented as reduced form versions of the original setting. Often, to focus on first-stage decisions, avoiding the chance of an influence of the second stage on the first one, the second stage is not modeled explicitly. Usually, this simplification is applied in experiments dealing with investment decisions in oligopolistic environments.[1]

In this paper, we implement a two-stage game as a two-stage experiment. We compare the results obtained in this fashion to those arising in an one-stage experiment, which reproduces a reduced form of the same game. To this end, we deal with the two-stage model and the corresponding one-stage experiment discussed in Sacco (2008). The analysis concerns the relation between the intensity

[1] See Suetens (2005), Halbheer et al. (2007), Sacco (2008) for experiments where the second stage, corresponding to Cournot competition, is not modeled explicitly.

of competition and process investments. We consider a game where duopolists with identical initial marginal costs choose cost-reducing investments in the first stage.[2] In the second stage, they engage in differentiated Cournot competition. An increase in competition corresponds to a reduction in product differentiation. It turns out that the relation between the intensity of competition and investments is U-shaped. As long as product differentiation is sufficiently strong, an increase in competition reduces investments. For sufficiently similar products, a further increase in competition yields higher investments.

In the two-stage experiment, where subjects take investment and output decisions, we analyze player behavior for two levels of competition (intermediate and strong).[3] As a result, underinvestment arises for both intensities of competition. Moreover, in contrast to the prediction, the switch from intermediate to strong competition does not increase investments. Interestingly, this paper does not support the results obtained through the one-stage experiment, where subjects only take investment decisions and earn the equilibrium profits corresponding to the resulting product market subgame. There, overinvestment arises for both intermediate and strong competition. Further, as predicted, higher intensity of competition leads to greater investments.

Indeed, the product market stage influences the investment stage. It is important to understand how. Underinvestment in stage one should be induced by an output level in stage two, which lies below the Nash equilibrium; because, for a lower output, cost-reduction is less valuable. In fact, for strong competition, subjects choose outputs below the Cournot equilibrium outcome (CEO).[4] However, the observed outputs are not sufficient to explain underinvestment. Played investments are even lower than the optimal investments resulting from the chosen outputs. For intermediate competition, underinvestment cannot be explained by outputs below the CEO. Rather, outputs lie above the Nash equilibrium reflecting best-response behavior to wrong beliefs. That is, subjects believe that the

[2] In addition, Sacco (2008) deals with the asymmetric case, where one firm is ex-ante ahead of the competitor.

[3] At the chosen level of intermediate competition, the U-shaped investment function shows its minimum. Strong competition corresponds to homogenous Cournot competition. In addition, Sacco (2008) considers a weak level of competition.

[4] Outputs below the CEO in a homogenous Cournot duopoly also arise in Huck et al. (2004). However, they deal with a one-stage Cournot experiment and are not concerned with investment decisions.

other players choose outputs below equilibrium and respond accordingly.[5]

Interestingly, higher intensity of competition does not affect investments but outputs which, in contrast to the prediction, are greater for intermediate than for strong competition.[6] Subjects choose higher output levels in the setting where the negative externalities of other players' choices on the own decisions are weaker.

There are few studies dealing with models implemented as two-stage experiments and we are not aware of papers which explicitly compare two-stage to one-stage experiments that refer to the same model. Isaac and Reynolds (1992) analyze a stochastic dynamic model, where firms invest in process R&D and compete in a product market. The cost-reduction is random and depends on the firm's amount of R&D. They show that a Schumpeterian competition emerges, which is characterized by costly innovation, falling prices, and rising concentration. Further, Jullien and Ruffieux (2001) deal with cost-reductions in competitive double auction markets, where firms can either invest in cost-reduction in a known way or develop a new technology with uncertain outcome. They show that prices converge towards the competition level. Finally, Suetens (2008) considers a R&D stage and a pricing stage to test whether R&D cooperation enhances price collusion. She deals with two treatments (no vs. complete spillovers) and finds out that, in general, prices are between the Nash equilibrium and the cooperative level.

This paper is structured as follows. Section 4.2 contains the theoretical framework. Section 4.3 describes the experimental design and results. Section 4.4 concludes.

4.2 The Model

Consider a two-stage game, where firms $i = 1, 2$ first engage in cost-reducing investments and then compete in the product market.[7] The inverse demand functions are given by

$$p_i = a - q_i - bq_j, \ i \neq j, \tag{4.1}$$

where $b \in [0, 1]$, and $a > 0$.

[5] Observe that in the Cournot game outputs are strategic substitutes.

[6] In contrast to Huck et al. (2004), where outputs increase in competition in the sense of a larger number of firms, we have outputs decreasing in the intensity of competition.

[7] The set-up corresponds to Sacco (2008).

For $b = 0$, equation (4.1) implies that both firms are monopolists. The case $b = 1$ corresponds to a homogenous Cournot market. Thus, the higher b the higher the intensity of competition.

Firms are ex-ante symmetric; that is, initial marginal costs are given by $c_i^0 = c^0$. In the first stage, firms simultaneously choose investments $y_i \in [0, c^0)$, resulting in marginal costs $c_i = c^0 - y_i$. The investment costs are quadratic and given by ky_i^2, where $k > 0$. In the second stage, firms simultaneously choose quantities, that is, they compete à la Cournot.

Backward induction shows that the net profit of firm $i = 1, 2$ in the first stage of the game is given by

$$\pi_i = \left(\frac{2(Y^0 + y_i) - b(Y^0 + y_j)}{4 - b^2} \right)^2 - ky_i^2, \; i \neq j, \tag{4.2}$$

where $Y^0 \equiv a - c^0 > 0$ represents the efficiency level.[8]

The maximization of (4.2) with respect to y_i leads to

$$\frac{\partial \pi_i}{\partial y_i} = \frac{8\left(Y^0 + y_i\right) - 4b\left(Y^0 + y_j\right)}{\left(4 - b^2\right)^2} - 2ky_i \equiv 0. \tag{4.3}$$

From the first-order condition (4.3), the following optimal relation between investments and outputs arises:

$$y_i = \frac{2q_i}{k(4 - b^2)}. \tag{4.4}$$

The second-order condition is given by

$$\frac{\partial^2 \pi_i}{\partial y_i^2} = \frac{8}{\left(4 - b^2\right)^2} - 2k < 0. \tag{4.5}$$

Note that (4.5) is fulfilled $\forall b \in [0, 1]$ if $k > \frac{4}{9}$.

From (4.3), it follows that

$$y_i = \frac{4Y^0 - 2b\left(Y^0 + y_j\right)}{k\left(4 - b^2\right)^2 - 4}. \tag{4.6}$$

Relation (4.6) implies the following equilibrium investments:

$$y_i^* = y^* = \frac{2Y^0}{k\left(2 + b\right)\left(4 - b^2\right) - 2}. \tag{4.7}$$

[8] Note that in the Cournot game the root of the gross profit, namely the term $\frac{2(Y^0 + y_i) - b(Y^0 + y_j)}{4 - b^2} \equiv q_i$, represents the optimal output level. Here and in the following, we assume that $2(Y^0 + y_i) - b(Y^0 + y_j) > 0$.

Next, we consider the specific parameterization used in the reduced-form experiment of Sacco (2008) that we will also implement in this experiment. Let $a = 50$, $k = 1$, and $c^0 = 21$. Figure 4.1 shows the plot of the equilibrium investments for $b \in [0, 1]$.

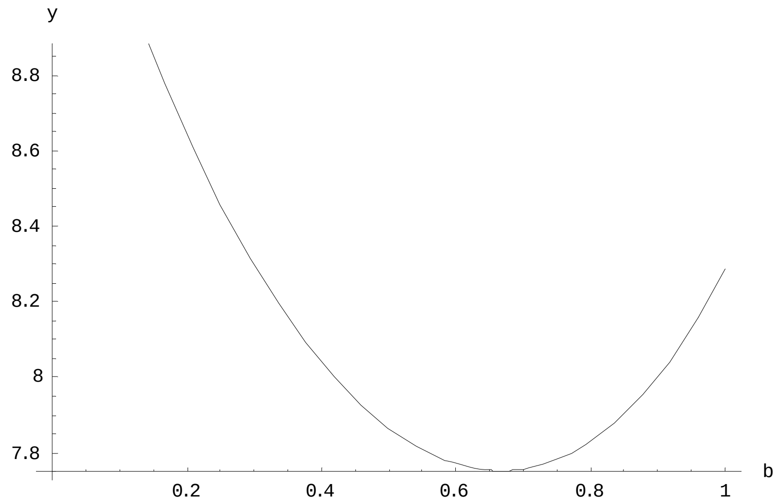

Figure 4.1: Investments of the firms.

In the experiment, we consider two cases for b, which correspond to different intensities of competition: $b = \frac{2}{3}$ (intermediate) and $b = 1$ (strong). For the two values of the competition parameter b, the following equilibrium investments arise:

$$\begin{cases} b = \frac{2}{3} \Rightarrow y^* = 7.75 \\ b = 1 \Rightarrow y^* = 8.28 \end{cases} . \tag{4.8}$$

Figure 4.1 reveals that, for both firms, there is a U-shaped relation between intensity of competition and investments. In particular, the switch from intermediate to strong competition leads to higher investments. The minimum of the investment function lies at $b = \frac{2}{3}$.

Further, the equilibrium outputs $q_i^* = q^*$ are given as follows:

$$\begin{cases} b = \frac{2}{3} \Rightarrow q^* = 11.77 \\ b = 1 \Rightarrow q^* = 12.43 \end{cases} . \tag{4.9}$$

As shown in (4.8) and (4.9), there is a positive relation between equilibrium investments and outputs; a cost reduction is more valuable for higher output levels.

4.3 The Experiment

4.3.1 Experimental Design and Procedures

The game implemented in the experiment exactly reproduces the described two-stage game. Subjects took investment and output decisions, which we restricted to $y_i \in \{0, 1, ..., 14\}$ and $q_i \in \{0, 1, ..., 19\}$, respectively.

In April 2008, we conducted two experimental sessions at the University of Zurich. Participants were undergraduate students.[9] Each session had 20 periods. There was a switch of the competition parameter after period 10. That is, participants played the game for one parameterization in the first ten periods and for the other parameterization in the last ten periods. In the two sessions, we reversed the order of the parameterizations to allow for sequencing effects. Table 4.1 gives an overview of the sessions.

Session	Period 1-10	Period 11-20
S1	$b = 0.67$	$b = 1$
S2	$b = 1$	$b = 0.67$

Table 4.1: Two sessions.

In S1, there were 36 subjects; in S2, 30. This led to a total of 1320 investment and equivalent output observations. Moreover, in each period, subjects were asked to give a belief about investment and output of the other group member.

No subject participated in more than one session. We built fixed matching groups of 6 subjects for statistical reasons. The participants were randomly matched into groups of size two within the matching groups. At the end of each period, subjects were informed about investment and output level of the other group member and their own net profit for that period. In each session, participants received an initial endowment of CHF 20 ($\approx$EUR 12). Average earnings including the endowment were CHF 30 ($\approx$EUR 19) for both S1 and S2. Sessions lasted about 2 hours each. The experiment was programmed and conducted with the software z-Tree (Fischbacher, 2007).

[9] We did not exclude any disciplines. We had students of law, engineering, psychology, economics etc.

4.3.2 Results

In this section, we discuss the experimental results. First, we analyze the investment stage; then, the output stage. For both stages, it turns out that the results concerning the first ten periods are very similar to those arising in the last ten periods. To avoid replication, we will focus on the first period range.[10]

The Investment Stage

In the following, we discuss the strong competition and the intermediate competition case in turn.

Strong competition First, we compare observed investments in the one-stage with those in the two-stage experiment.

Result 22 *Under strong competition, mean investments are higher for one stage than for two stages.*

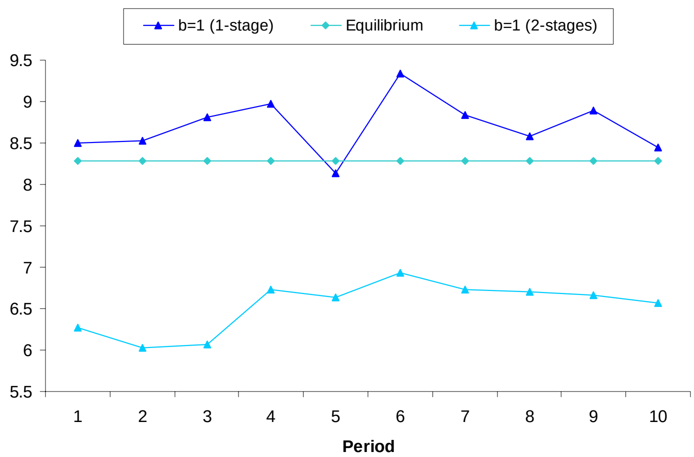

Figure 4.2: One stage vs. two stages: Mean investments for $b = 1$.

Figure 4.2 reveals that investments are clearly higher in the one-stage than in the two-stage case; a regression over a constant and a Wilcoxon rank sum test show high significance ($p < 0.01$). Further, there is overinvestment for one

[10]The choice of the period range has to do with the fact that in Sacco (2008) the analyzed effects are stronger in the first ten than in the last ten periods.

stage and underinvestment for two stages. As shown in Sacco (2008) for the one-stage case, overinvestment reflects wrong beliefs that subjects have about the investments of the other players. Subjects believe that the others invest less than they actually do and thus overinvest.[11] To a large extent, subjects play best response to the own wrong beliefs. In the two-stage case, underinvestment is not driven by overestimated beliefs about investments. In fact, there is no significant difference between investments and corresponding beliefs (see Figure 4.3). Rather, the underinvestment in stage one appears to result because subjects correctly anticipate that their second-stage output will be lower than the CEO, and, accordingly, they invest less than in the subgame perfect equilibrium. To make this idea precise, we introduce some useful terminology.

Definition 3 *$y_i^*(q_i)$ is player's i optimal investment level in stage one if player i chooses the output level q_i in stage two. Relation (4.4) for $k = 1$ implies*

$$y_i^*(q_i) = \frac{2q_i}{4 - b^2}. \tag{4.10}$$

Further, we define

$$\bar{y}^*(\bar{q}) = \frac{2\bar{q}}{4 - b^2} \tag{4.11}$$

as the optimal mean investment level in stage one if $\bar{q}$ is the played mean output level in stage two.

Definition 3 shows, for given second-stage outputs, the optimal investment levels in the first stage.[12] We abstract from the fact that subjects' investment choices may influence the output choices of the other players.

Using Definition 3, we characterize the relation between the observed mean investment level denoted as $\bar{y}$ and the played mean output level $\bar{q}$.

Result 23 *Under strong competition, $\bar{q} < q^*$ in stage two leads to $\bar{y} < \bar{y}^*(\bar{q}) < y^*(q^*)$ in stage one.*

Subjects choose investments according to the expectations that they have about their own outputs. However, outputs below the CEO are not sufficient to explain underinvestment. In fact, $\bar{y}$ is even lower than $\bar{y}^*(\bar{q})$. This is shown in Figure 4.3. Over the period range, the dotted line represents (4.11) for $b = 1$.

[11] Note that investments and corresponding beliefs are strategic substitutes.
[12] Note that relation (4.11) holds because the mean investment level only depends on players' total output.

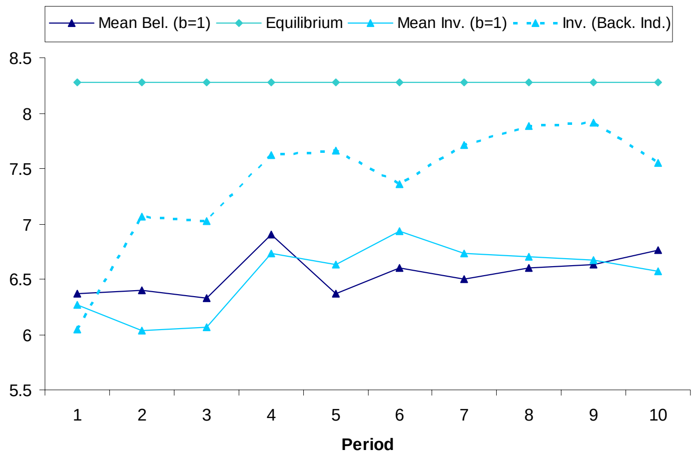

Figure 4.3: Investments and beliefs for $b = 1$.

Intermediate competition For intermediate competition, the two-stage experiment also leads to lower investments than in the one-stage case.

Result 24 *Under intermediate competition, mean investments are higher for one stage than for two stages.*

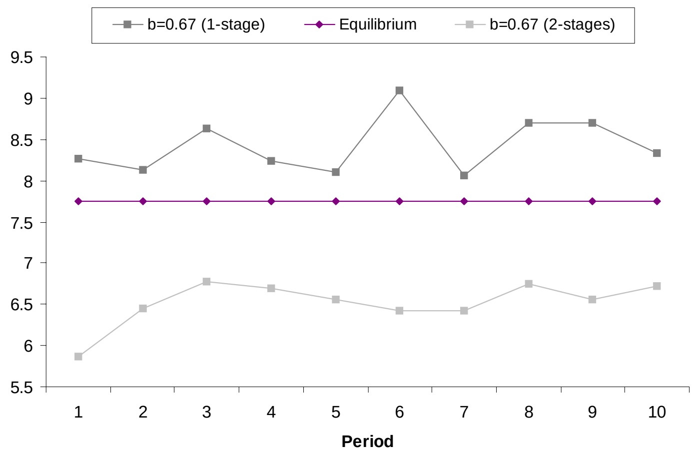

Figure 4.4: One stage vs. two stages: Mean investments for $b = 0.67$.

Figure 4.4 reveals that, like for strong competition, the difference between one-stage and two-stage investments is substantial.[13] Again, beliefs about other players' investments do not affect own investments (see Figure 4.5). However, in contrast to strong competition, underinvestment in stage one is not implied by outputs below the CEO in stage two.

Result 25 *Under intermediate competition, $\bar{y} < y^*(q^*)$ in stage one does not result from $\bar{q} < q^*$ in stage two.*

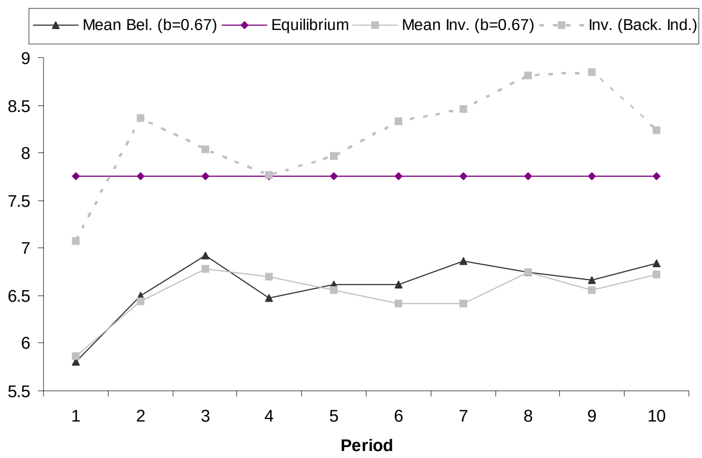

Figure 4.5: Investments and beliefs for $b = 0.67$.

In fact, played outputs lie above the CEO, which should lead to overinvestment. The dotted line in Figure 4.5 represents the optimal investments implied by (4.11) for $b = 0.67$.[14]

Another interesting aspect concerns the investment increase predicted by the model when switching from intermediate to strong competition. In the one-stage experiment, this increase in competition indeed has a positive effect on investments. However, the two-stage experiment does not yield the same result.

Result 26 *In the two-stage case, higher intensity of competition does not increase investments.*

[13] A regression over a constant and a Wilcoxon rank sum test show that the investment difference is highly significant.

[14] The deviation of observed investments from the optimal investments obtained by backward induction from the played outputs is more pronounced under intermediate than strong competition.

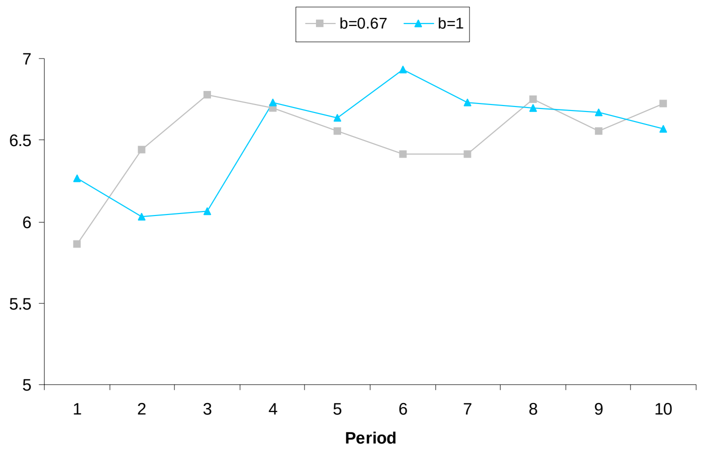

Figure 4.6: Investments for $b = 0.67$ and $b = 1$.

Figure 4.6 shows that, for the two intensities of competition, investments are close; over the period range, the difference is not significant.[15]

The Output Stage

In the following, we provide an explanation for the fact that, in spite of the output difference between intermediate and strong competition – in the former case outputs lie above the CEO, in the latter case below the CEO – underinvestment arises for both intensities of competition. As in the previous section, we start with the strong competition case.

Strong competition To illustrate the output behavior, consider first the following definition.

Definition 4 *$q_i^*(y_i, y_j)$ is player's i optimal output level in stage two if players i and j choose the investment levels y_i and y_j in stage one, respectively. From Section 4.2, we have*

$$q_i^*(y_i, y_j) = \frac{2(Y^0 + y_i) - b(Y^0 + y_j)}{4 - b^2}. \tag{4.12}$$

Further, analogously to (4.11), we define

$$\bar{q}^*(\bar{y}) = \frac{(2 - b)(Y^0 + \bar{y})}{4 - b^2} \tag{4.13}$$

[15] Over all considered periods and subjects, the mean investment is 6.52 for $b = 0.67$ and 6.53 for $b = 1$.

as the optimal mean output level in stage two if $\bar{y}$ is the played mean investment level in stage one.

Next, we characterize the played outputs.

Result 27 *Under strong competition, mean outputs converge towards $\bar{q}^*(\bar{y})$.*

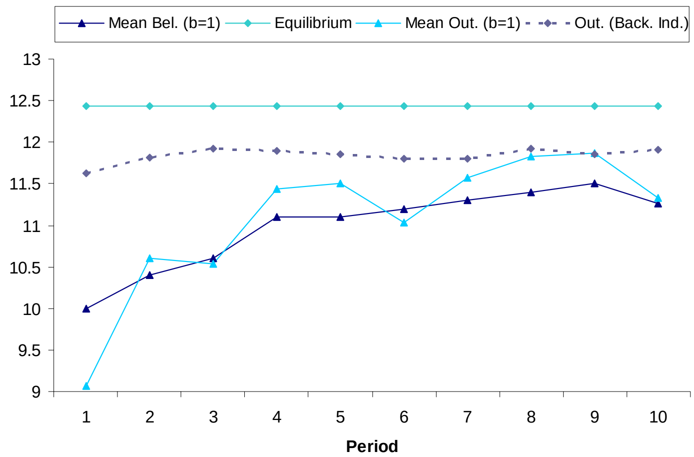

Figure 4.7: Outputs and beliefs for $b = 1$.

Figure 4.7 reveals that played outputs are not affected by the beliefs about other players' outputs.[16] Further, we see that observed outputs converge towards the optimal level that follows from the chosen investments. In the last five periods of the considered range, there is no significant difference.

The fact that the relation between the two stages drives subject behavior is reinforced by the following considerations. First, for individual decisions, there is a significantly positive relation between own investments and outputs ($p < 0.01$). However, the regression line referring to the actual relation is flatter than the optimal relation line.[17] This is shown in Figure 4.8. Second, there is a significantly negative relation between other players' investments and own outputs ($p = 0.045$). However, the optimal relation line is steeper.[18] This is shown in Figure 4.9.

[16] The difference between outputs and corresponding beliefs is not significant.

[17] By (4.10), the slope of the optimal relation line is given by $\frac{2}{3}$.

[18] It is easy to check from the equilibrium output that the slope is $-\frac{1}{3}$. The intercept is arbitrary chosen as 10.

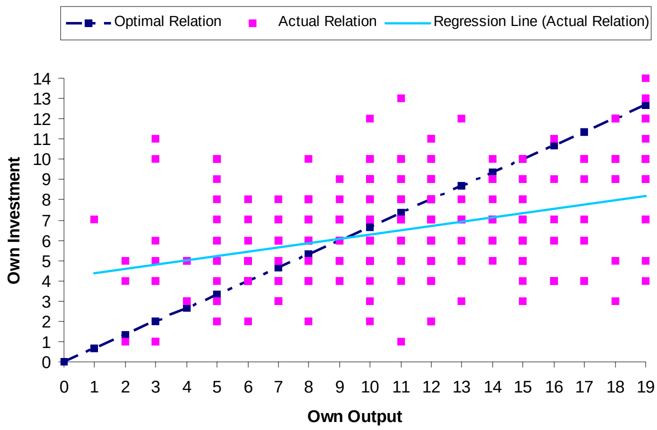

Figure 4.8: Relation between own investments and outputs.

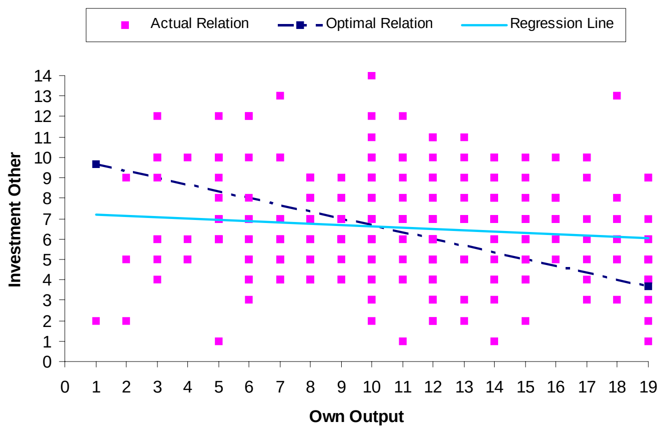

Figure 4.9: Relation between other players' investments and own output.

Intermediate competition Interestingly, for intermediate competition, underinvestment is not driven by outputs below the CEO. Rather, outputs lie above equilibrium. In the following, we provide an explanation for the output behavior in stage two. To this end, consider the following definition.

Definition 5 $q_i^*(y_i, B_i(q_j))$ *is player's i best response to the own belief about player's j output in stage two, given that* y_i *is player's i investment level in stage one. In other words,*

$$q_i^*(y_i, B_i(q_j)) = \arg\max_{q_i} \; (a - q_i - bB_i(q_j) - c_i)q_i. \tag{4.14}$$

Further, we define $q^*(\bar{y}, \bar{B})$ *as players' best response to the own mean beliefs about other subjects' output in stage two, given that* $\bar{y}$ *is the mean investment level in stage one.*

Now, we characterize the output behavior.

Result 28 *Under intermediate competition, mean outputs converge towards* $q^*(\bar{y}, \bar{B})$.

In contrast to strong competition, beliefs about other players' outputs have an impact on own output choices (see Figure 4.10). This explains the output behavior in stage two. However, the inconsistency between played investments and outputs obviously still holds.

Unlike investment decisions, the switch from intermediate to strong competition affects output choices. Subjects play higher output levels in the setting where the negative externalities resulting from the other players are weaker.

Result 29 *In the two-stage case, higher intensity of competition decreases mean outputs.*

Figure 4.11 reveals that, in each period of the considered range, in contrast to the prediction, outputs are higher for intermediate than for strong competition; the difference is highly significant.

Individual decisions confirm the explanation provided above. Figure 4.12 shows the relation between own investments and outputs. In line with the strong

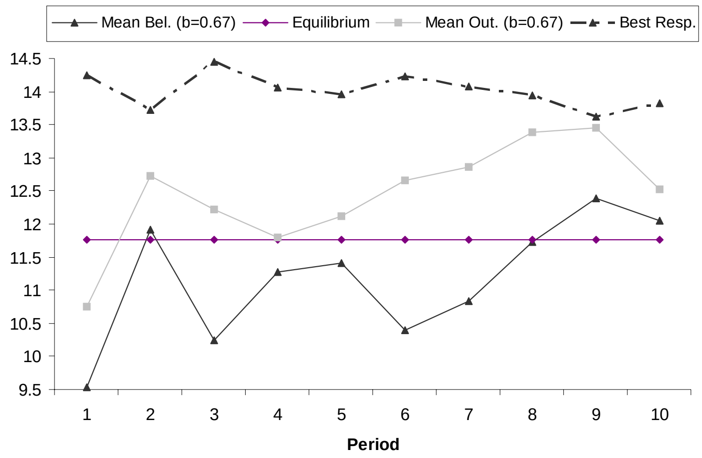

Figure 4.10: Outputs and beliefs for $b = 0.67$.

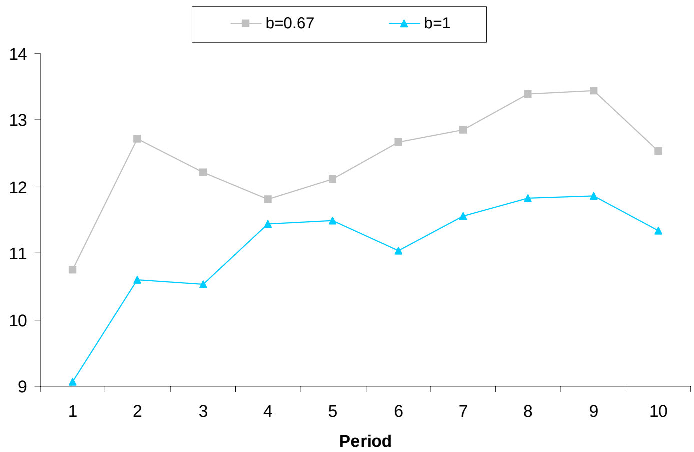

Figure 4.11: Outputs for $b = 0.67$ and $b = 1$.

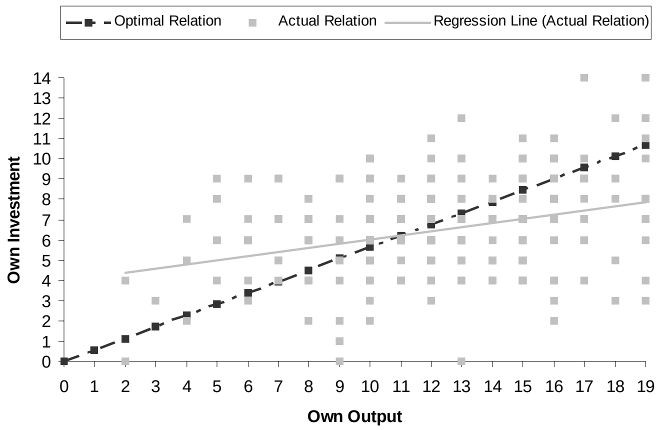

Figure 4.12: Relation between own investments and outputs.

competition case, there is a significantly positive relation between own investments and outputs ($p < 0.01$). Again, the actual relation regression line is flatter than the optimal relation line.[19]

For intermediate competition, consistently with Result 28, one may expect that other players' investments have a different impact on own output choices than for strong competition. In fact, the negative relation between investments of the other players and own outputs obtained in the strong competition case does not emerge for intermediate competition. Rather, the relation is significantly positive ($p = 0.093$). This is revealed in Figure 4.13.[20]

Summing up, for intermediate competition, subjects tend to neglect the investments of the other players and focus more on stage two. For strong competition, investment choices are consistent with output decisions.

4.4 Conclusion

We compared the results obtained through a two-stage experiment to those arising from an one-stage experiment implementing the same two-stage model. We considered a duopoly game which deals with the relation between the intensity of competition and process investments. In the first stage, ex-ante symmetric duopolists choose cost-reducing investments; in the second stage, they engage in

[19]The slope of the optimal relation line is $\frac{9}{16}$.

[20]The optimal relation line shows a slope of $-\frac{3}{16}$. The intercept is arbitrary chosen as 9.

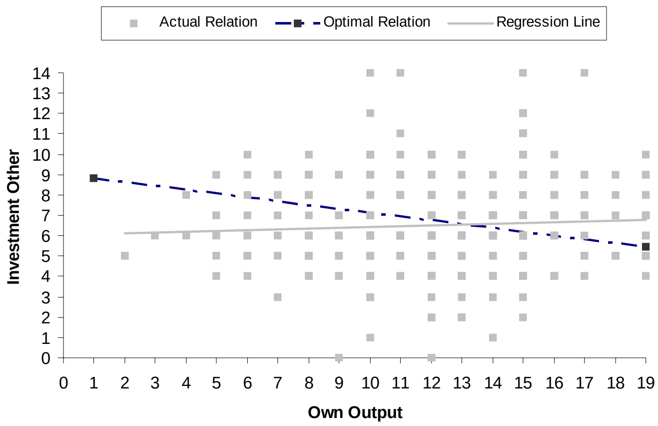

Figure 4.13: Relation between other players' investments and own output.

differentiated Cournot competition. An increase in competition corresponds to a reduction in product differentiation.

In the one-stage experiment, where subjects only take investment decisions, there is overinvestment for both intermediate and strong competition. Further, as predicted, an increase in competition yields higher investments.

Interestingly, the two-stage experiment, where subjects take investment and output decisions, does not support the one-stage results. For both intermediate and strong competition, there is underinvestment; further, an increase in competition does not lead to higher investments.

Underinvestment in stage one should be induced by outputs below the CEO in stage two. Indeed, this arises for strong competition. Rather, for intermediate competition, outputs lie above equilibrium reflecting best-response behavior to wrong beliefs about other players' outputs. Subjects choose higher output levels in the setting where decisions of other players have a weaker impact on own choices.

Acknowledgement For helpful comments and suggestions, I am grateful to Armin Schmutzler and to participants at the following conferences: ESA (Pasadena) and EEA (Milan).

References

Fischbacher, U.: "Z-Tree. Toolbox for Readymade Economic Experiments." *Experimental Economics* 10(2), 171-178 (2007).

Halbheer, D., Fehr, E., Götte, L., Schmutzler, A.: "Self-Reinforcing Market Dominance." *SOI Working Paper*, No. 711, University of Zurich (2007).

Huck, S., Normann, H.T., Oechssler, J.: "Two are Few and Four are Many: Number Effects in Experimental Oligopolies." *Journal of Economic Behavior and Organization* 53(4): 435-446 (2004).

Isaac, R.M., Reynolds, S.S.: "Schumpeterian Competition in Experimental Markets." *Journal of Economic Behavior and Organization* 17: 59-100 (1992).

Jullien, C., Ruffieux, B.: "Innovation, Avantages Concurrentiels et Concurrence." *Revue d'Economie Politique* 111(1): 121-150 (2001).

Sacco, D.: "Is there a U-shaped Relation between Competition and Investment?" *SOI Working Paper*, No. 808, University of Zurich (2008).

Suetens, S.: "Cooperative and Noncooperative R&D in Experimental Duopoly Markets." *International Journal of Industrial Organization* 23: 63-82 (2005).

Suetens, S.: "Does R&D Cooperation Facilitate Price Collusion? An Experiment." *Journal of Economic Behavior and Organization* 66: 822-836 (2008).

Curriculum Vitae

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